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THESIS

Radiation Surveys of the
Naval Postgraduate School LINAC

by
David Franklin Davidson
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Thesis Advisor: Xavier K. Maruyama

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The NPS LINAC was initially designed for use in radiation damage and nuclear structure studies. The LINAC's role has subsequently evolved to include research in a variety of other areas such as the generation of coherent microwave, optical, and x- radiation. The use of high energy electrons produces a radiation environment for which personnel and equipment safety must be addressed.

It is the purpose of this study to measure the radiation levels in the areas surrounding the LINAC and to identify the sources of that radiation. A guide is provided for the installation of additional supplemental shielding for the LINAC to further reduce radiation levels in areas occupied by personnel.

Primary conclusions of this study are that the radiation levels produced by the linear accelerator are below statutory limits, and that a neutron energy correction factor different than currently used should be used for personnel dosimetry at the NPS LINAC. This will result in the reduction of the TLD measured neutron dose evaluation for personnel.

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Radiation Surveys of the Naval Postgraduate School LINAC

by

David Franklin Davidson
Lieutenant, United States Navy
B.S., The Citadel, 1983

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the degree of

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Author: D. F. Davidson
David F. Davidson

Approved by: Xavier K. Maruyama
Xavier K. Maruyama, Thesis Advisor

David Scott Davis
D. Scott Davis, Second Reader

K. E. Woehler
Karlheinz E. Woehler, Chairman,
Department of Physics

ABSTRACT

The NPS LINAC was initially designed for use in radiation damage and nuclear structure studies. The LINAC's role has subsequently evolved to include research in a variety of other areas such as the generation of coherent microwave, optical, and x-radiation. The use of high energy electrons produces a radiation environment for which personnel and equipment safety must be addressed.

It is the purpose of this study to measure the radiation levels in the areas surrounding the LINAC and to identify the sources of that radiation. A guide is provided for the installation of additional supplemental shielding for the LINAC to further reduce radiation levels in areas occupied by personnel.

Primary conclusions of this study are that the radiation levels produced by the linear accelerator are below statutory limits, and that a neutron energy correction factor different than currently used should be used for personnel dosimetry at the NPS LINAC. This will result in the reduction of the TLD measured neutron dose evaluation for personnel.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

The Naval Postgraduate School Linear Accelerator (LINAC) was initially designed for use in radiation damage and nuclear structure studies and became operational in September of 1966. The LINAC's role has subsequently evolved to include research in various areas, including inelastic electron scattering and the generation of stimulated Cerenkov microwave radiation and x- radiation. A brief description of the linear accelerator is provided in Appendix A.

Electrons are injected into the accelerating sections of the LINAC with a kinetic energy of 80 keV, where radio frequency (R.F.) power then accelerates the electrons to final energies of up to 100 MeV. This acceleration process leads to an unavoidable energy and spatial spread in the electron beam. Experimental accuracy, however, requires that the electron beam be tailored to acceptable energy resolutions through use of a beam optics system. The interaction of the high energy electrons with the beam optics and energy selection system produces a gamma ray bremsstrahlung spectrum with an energy maximum equal to that of the accelerated electrons. This gamma radiation can interact with surrounding matter to produce neutron radiation.

High energy gamma and neutron radiation is directed in a narrow cone centered about the path of the original electron beam.

However, subsequent interactions result in multiple scattering, and the radiation will appear distributed over all angles.

Radiation can produce adverse physiological effects in human beings, and it can cause electronic equipment to malfunction. It is therefore necessary to insure that the radiation levels in the areas adjacent to the LINAC do not exceed an acceptable level. Soper [Ref. 1] conducted the initial radiation survey of the LINAC and surrounding areas in 1967, and provided a guide for the shielding of the LINAC. Zurey [Ref. 2], in 1985, conducted a radiation survey of the LINAC to verify reduction in radiation levels following installation of supplementary lead and borated paraffin shielding on the LINAC tunnel roof. It has been the purpose of this thesis study to determine if the radiation levels in the areas surrounding the LINAC have since increased beyond acceptable limits. A further purpose has been to provide a guide, as necessary, for the installation of additional supplemental shielding for the LINAC to further reduce these radiation levels.

The reader may wish to read Appendix B prior to proceeding with the main body of this thesis, as that appendix addresses general introductory material.

II. LINAC RADIATION LEVELS

A. CONTROL ROOM

Since the LINAC control room is the only manned station during operation, the radiation levels there are of primary concern. Radiation measurements were taken for a series of six runs each at electron energies of 30, 60, and 90 MeV. Three of the six runs were with the energy defining slit width[1] set at 100, corresponding to an electron energy resolution of 0.30%. The other three were with the slit width set at 300, corresponding to a resolution of 1.14%. This was to determine the effect of slit width on the radiation levels in the control room. The data for this survey are contained in Appendix G.

1. Gamma Radiation Levels

Table 1 shows the average values for the gamma radiation levels at each set of electron energy and slit width configurations.[2] Figure 1 depicts these values graphically. There is a significant

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[1] The slits are remotely controlled from the control room, and have a turn counter that allows the slit separation to be set from zero to two inches. In 1967 Midgarden, [Ref. 3], determined that a slit width of 0.125 inches corresponded to an energy spread of about 0.50%. During the LINAC staff's slit calibration of August 19, 1971, the fractional energy spread, in percent, was determined to be equal to 0.0042 times the counter value, minus 0.124, or

$$\Delta E / E\,(\%) \cong (0.0042 \times \text{counter value}) - 0.124.$$

From these sources, the author estimates the counter value to be approximately equal to the separation, in thousandths of inches, of the slits. Numbers in this thesis that specify a slit width are the counter value and do not have associated units.

[2] This value is obtained by taking the average of the last column of Appendix E, Tables E1 through E6, and normalizing that average to the electron energy.

spread in these averages due to the dependence of the gamma radiation levels on the tuning of the electron beam. That dependence is not discussed in this thesis. From these data, it is noted that there is no significant dependence of the gamma radiation level on the slit width. However, the data do show a dependence of the gamma radiation level on the electron energy. As the electron energy is increased, i.e., as the second and third accelerator sections are brought on-line, the gamma radiation level in the control room decreases, as is easily seen in Figure 1. This is due to the increased electron transport efficiency at higher electron energy, which reduces the number of interactions between the electrons and the matter of the first accelerator section. This is plausible because when the first and second accelerator sections are on-line electron capture by the beam is more efficient, and, therefore, the beam has a smaller angular spread. In Table 1, the power is the electron beam power, e.g., 0.1 microamps at 100 MeV corresponds to 0.1 watt beam power.

For both gamma and neutron radiation, the fact that the radiation levels are slit independent suggest that the primary source of radiation in the control room is not due to electrons striking the slits.

TABLE 1: LINAC CONTROL ROOM AVERAGE GAMMA RADIATION LEVELS

Electron Energy (MeV)	Slit Width	Average Level (mrem/hr/watt)
30	300	0.084 ± 0.011
30	100	0.094 ± 0.017
60	300	0.016 ± 0.001
60	100	0.022 ± 0.005
90	300	0.012 ± 0.001
90	100	0.012 ± 0.001

Note: As measured with AN/PDR-27 and IM-231 B/PD Eberline RO-2 radiacs.

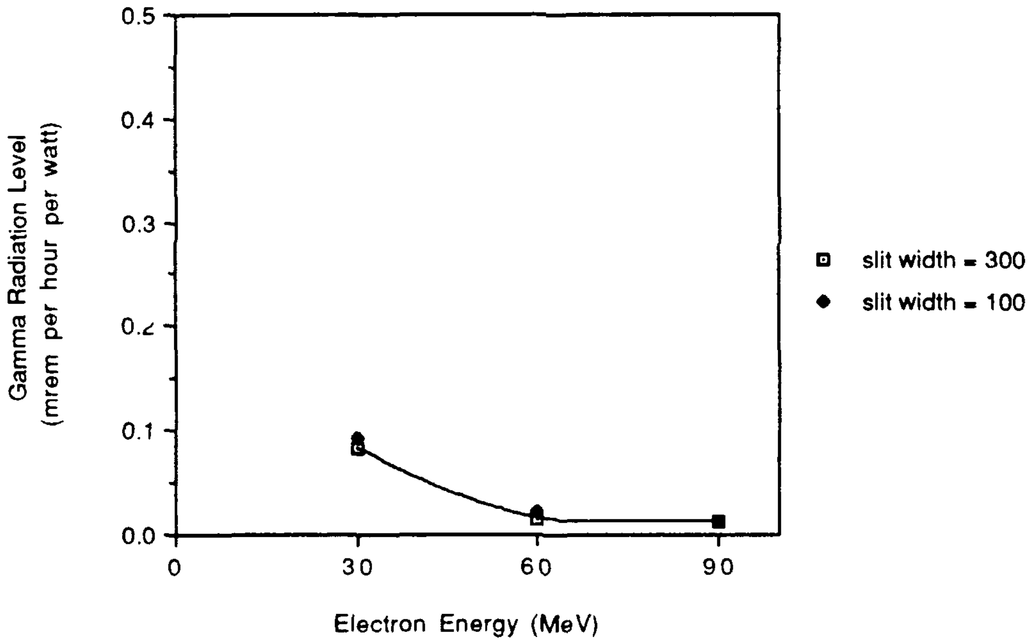

Figure 1: LINAC control room average gamma radiation levels. The gamma radiation level, normalized to the power of the electron beam, should be a constant value when plotted against the electron energy. The departure of this data from the expected value at 30 MeV is due to the inefficient electron transport at that energy. The plotted results are obtained from the data in Appendix G.

2. Neutron Radiation Levels

Table 2 shows the average values for the neutron radiation levels, as measured by AN/PDR-70 radiacs, at each set of electron energy and slit width configurations.[3] Figure 2 depicts these values graphically. There is a moderate spread in these averages for the same reason as discussed above. Again it is noted that there is no significant overall dependence of the neutron radiation level on the slit width and that as the electron energy is increased the neutron radiation level decreases. Note that in this instance the measured data are consistent with the expected results for energies of 60 to 90 MeV. The marked difference at 30 MeV is indicative of a lower electron transport efficiency when only the first accelerator section is on-line.

TABLE 2: LINAC CONTROL ROOM AVERAGE NEUTRON RADIATION LEVELS

Electron Energy (MeV)	Slit Width	Average Level (mrem/hr/watt)
30	300	0.27 ± 0.03
30	100	0.31 ± 0.02
60	300	0.033 ± 0.003
60	100	0.020 ± 0.004
90	300	0.030 ± 0.003
90	100	0.030 ± 0.002

Note: As measured with AN/PDR-70 radiac.

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[3] This value is obtained by taking the average of the last column of Appendix F, Tables F1 through F6, and normalizing that average to the electron energy.

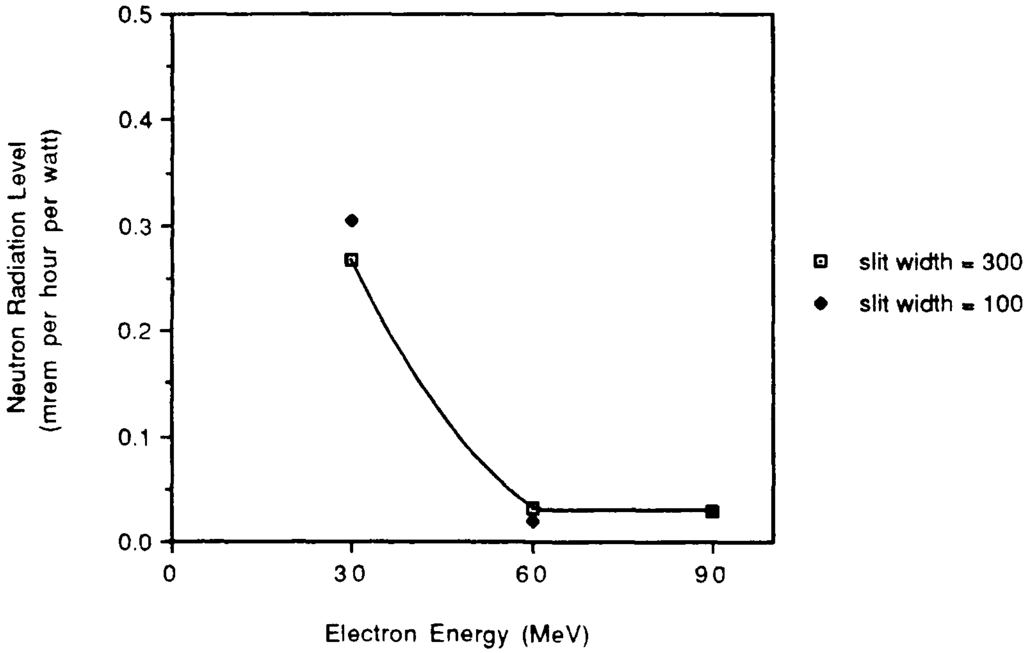

Figure 2: LINAC control room average neutron radiation levels. As with the gamma radiation measurement, the higher relative neutron radiation levels at 30 MeV indicate inefficient electron transport at lower energies. The plotted results are obtained from Table 2.

3. Total Radiation Level

The total radiation level in the LINAC control room is obtained by summing the gamma and neutron radiation levels. Table 3 shows these values numerically while Figure 3 depicts them graphically. It should be again noted that these values are averages, with a significant spread, and that these values are dependent on the tuning of the electron beam. Since the electron beam has a poorer transport efficiency at lower energies, the relative radiation levels at 30 MeV are higher.

The source of the radiation level in the control room is not primarily the LINAC endstation, but the first accelerator section and the ten foot lens.

TABLE 3: LINAC CONTROL ROOM RADIATION LEVEL (TOTAL)

Electron Energy (MeV)	Slit Width	Total Level (mrem/hr/watt)
30	300	0.35 ± 0.03
30	100	0.40 ± 0.03
60	300	0.049 ± 0.003
60	100	0.042 ± 0.006
90	300	0.041 ± 0.003
90	100	0.043 ± 0.002

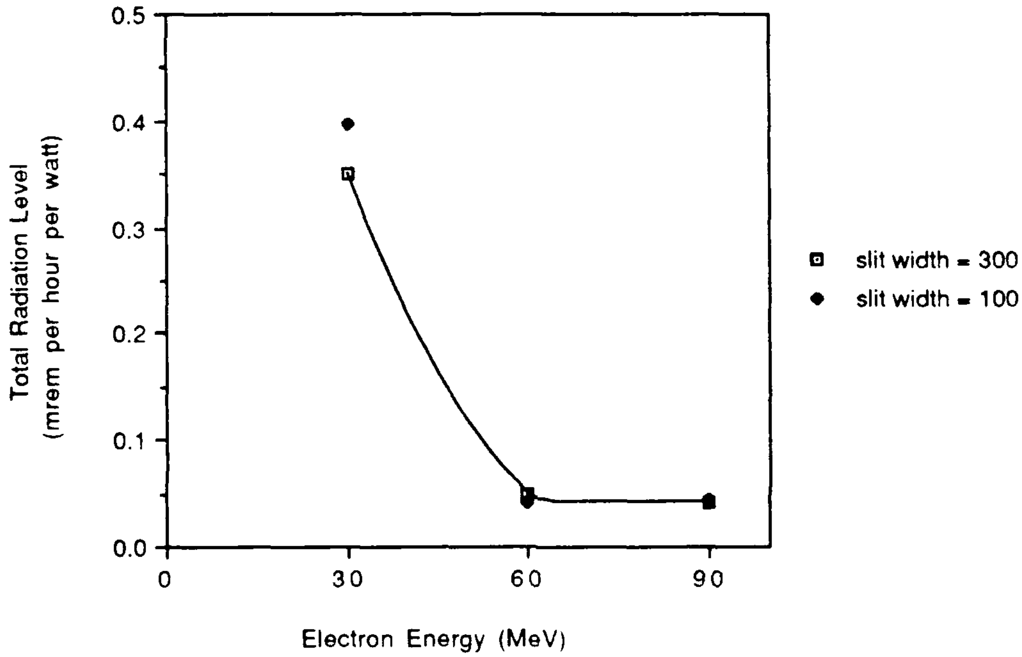

Figure 3: LINAC control room total radiation levels. The total radiation level is the sum of the neutron and the gamma radiation levels. The fact that the 100 slit width value at 30 MeV is slightly higher than the 300 slit width value is not of great significance since the plotted values are averages.

B. HALLIGAN HALL -- BASEMENT (ROOM 001)

In order to provide an accurate assessment of the shielding placed around the sides of the LINAC, radiation surveys were conducted in several areas, as shown on Figure 4. The survey conducted using points 1 through 42 was done while the LINAC's electron gun was off, i.e., dark current. It is estimated that the dark current was less than 0.5 nanoamps All of the other measurements in the basement of Halligan Hall were at normal operating parameters.

1. LINAC Sides

This survey was conducted, using points 1 through 42, at a height of 44 inches above the floor. The measurements of the AN/PDR-70 radiac are shown in counts per minute, due to the extremely low amount of neutron radiation present when the LINAC is operating with dark current. As shown in Figure 5, the gamma radiation level, in counts per minute, is almost identical to the radiation level in millirem per hour, so that the measured neutron radiation level is considered to be a valid representation of the true level. Figures 5 and 6 show the results of the gamma and neutron radiation levels, respectively, for the side of the LINAC closest to the control room. As is easily seen in these figures, there is a peak level between survey point positions 9 and 14. This radiation has as its source the first accelerator section and the ten foot lens. It exits the LINAC housing through a gap, from positions 9 through 13,

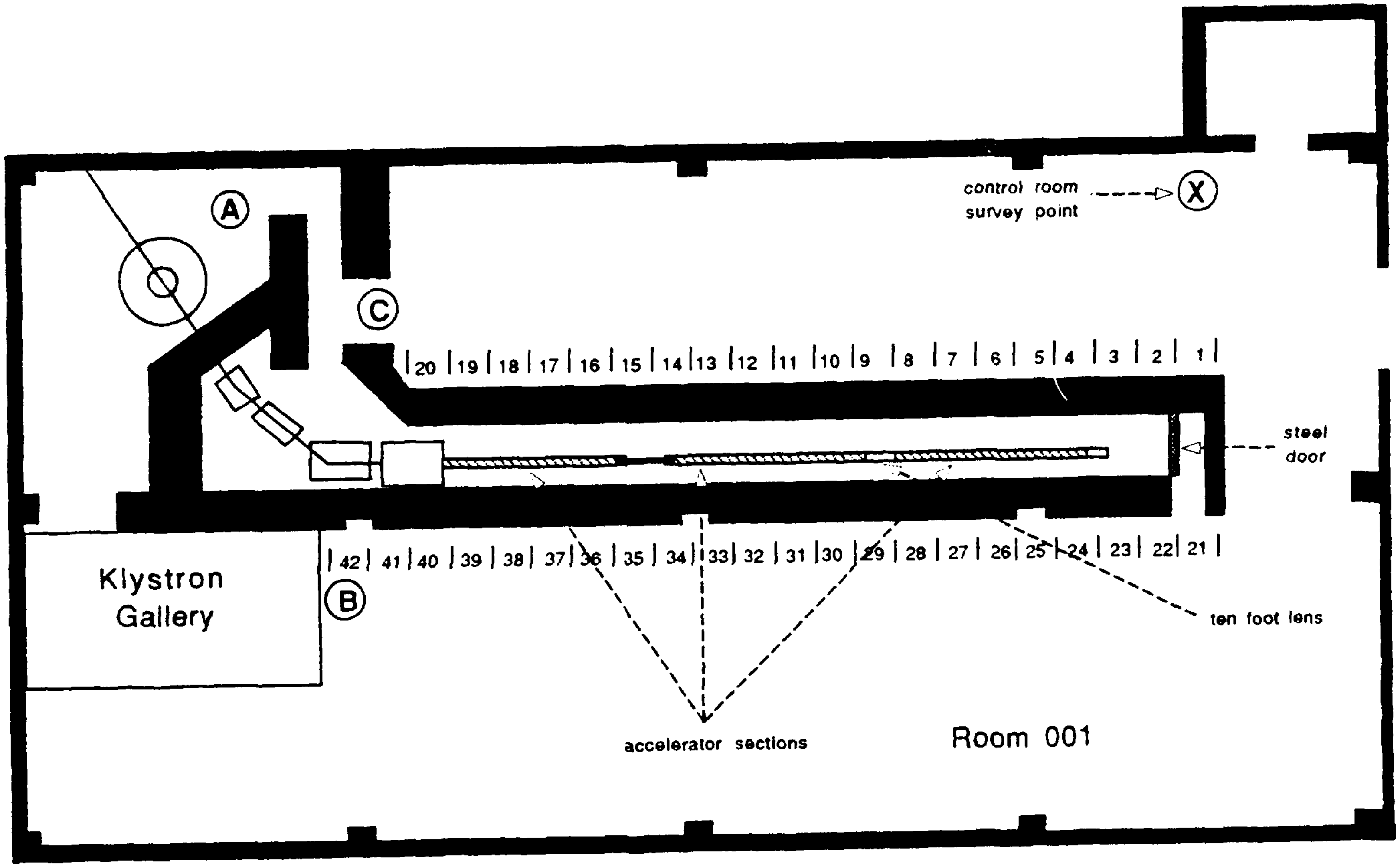

Figure 4: Position of survey points in Halligan Hall basement.

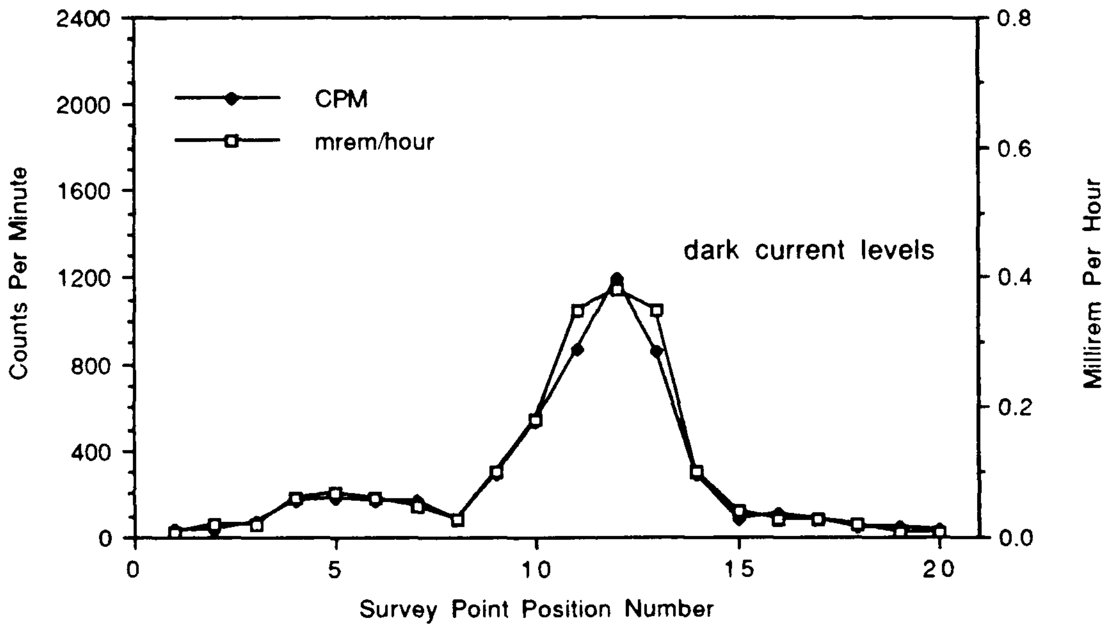

Figure 5: LINAC (control room side) gamma radiation level. The peak at position number 12 is from the first accelerator section and the upstream end of the ten foot lens. There is a gap in the supplemental shielding from positions 9 through 13 which allows this radiation to exit the LINAC housing. These measurements were taken at electron energies of 90 MeV.

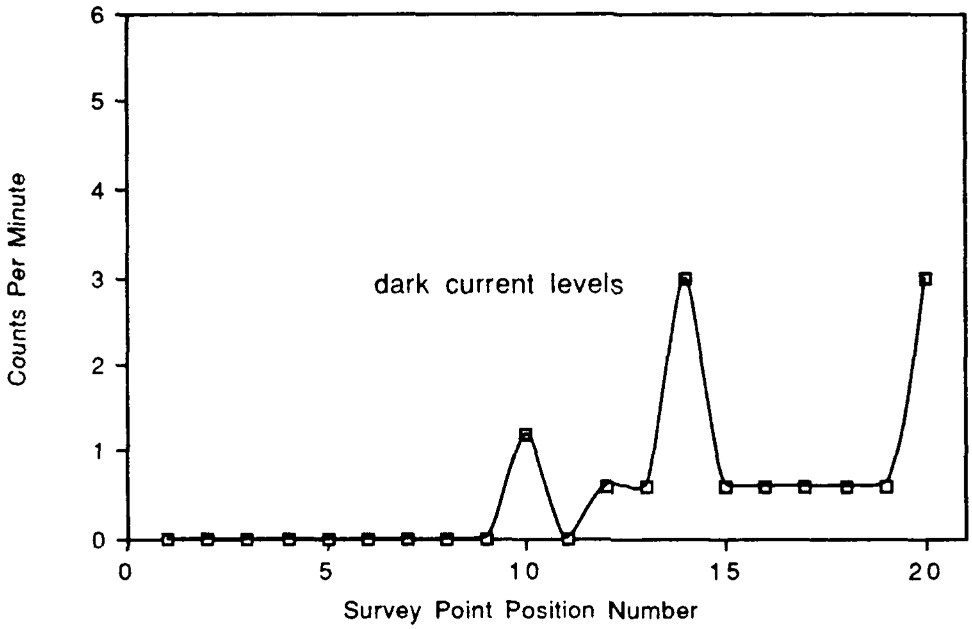

Figure 6: LINAC (control room side) neutron radiation level. Note that, as seen with the gamma radiation, the neutron radiation level shows a peak at positions 9 through 15 where there is a gap in the supplemental shielding. The increased level at position 20 is due to the radiation produced in the endstation. These measurements were made at electron energies of 90 MeV.

in the installed supplemental shielding on the control room side of the LINAC. This problem is addressed later.

Figures 7 and 8 show the results of these measurements for the side that is farthest from the control room. These figures show an overall increased radiation level due to the lesser amount of supplemental shielding installed on this side of the LINAC. There is a peak in the radiation levels shown on Figures 7 and 8, at survey point positions 30 through 35 that corresponds to the peak noted on the control room side of the LINAC. This shows the symmetry of the radiation field produced by the first accelerator section and the ten foot lens.

2. Other Basement Locations

Three other survey points were selected in the basement area to provide comparative data to the studies of Soper and Zurey. These points are shown on Figure 4 as circled letters. The measurements taken at these data points were made with the LINAC operating at 90 MeV and a current of 0.12 microamps. The results of the surveys taken at these data points are shown in Section II.D.

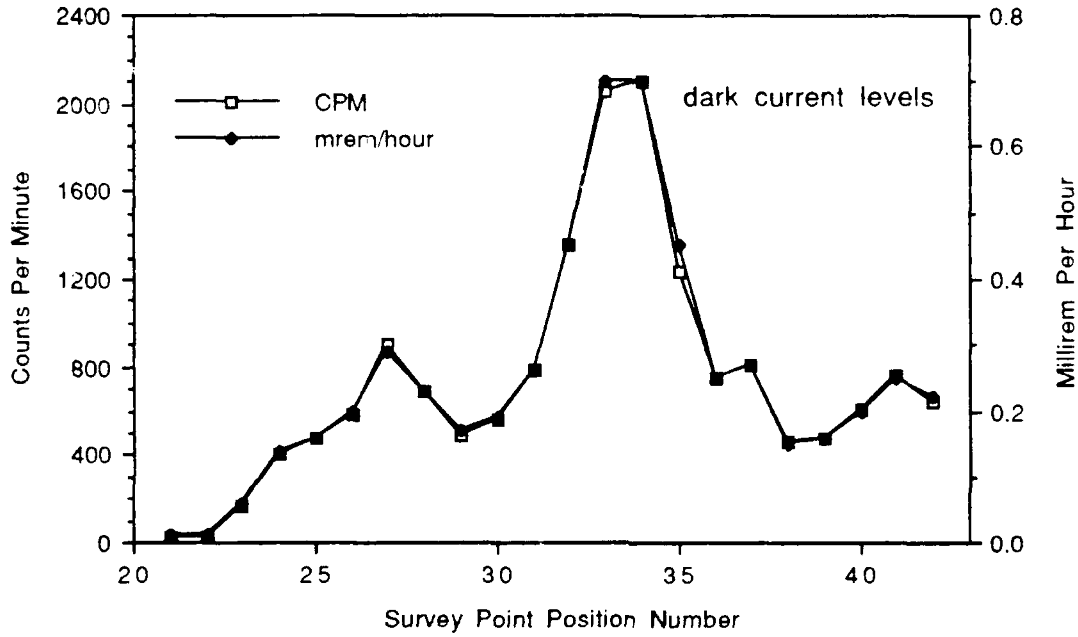

Figure 7: LINAC (far side) gamma radiation level. The higher radiation level on this side of the LINAC is due to a lesser amount of installed supplemental shielding. The peak values are at corresponding positions as on the control room side, showing the symmetry of the radiation field. These measurements were taken at electron energies of 90 MeV.

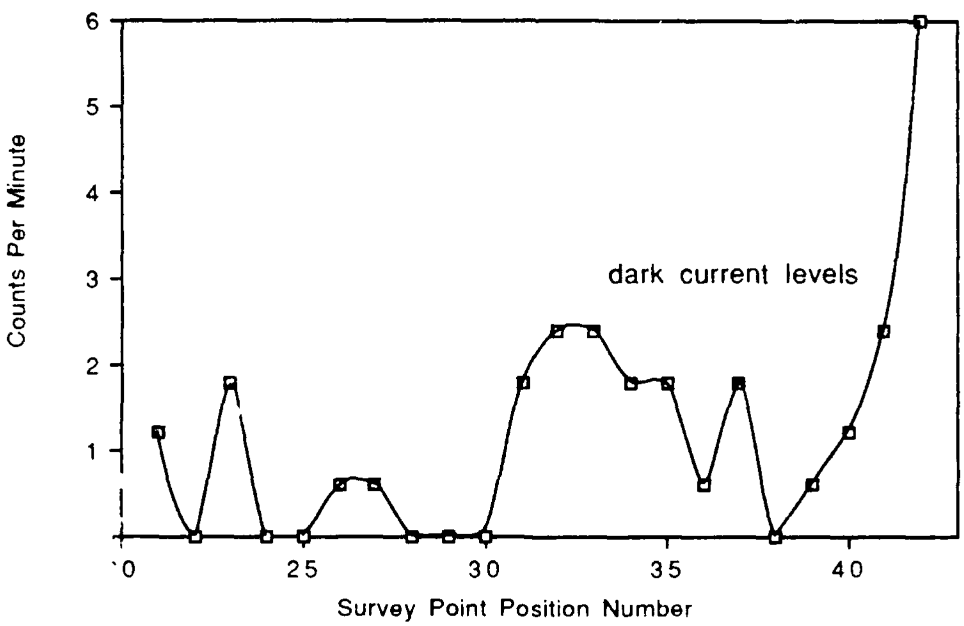

Figure 8: LINAC (far side) neutron radiation level. Note the peak at a corresponding position as on the gamma radiation level on this side of the LINAC. The increased levels at positions 40 through 42 are due to the radiation produced in the endstation. These measurements were taken at electron energies of 90 MeV.

C. HALLIGAN HALL -- FIRST FLOOR

The radiation levels in the area immediately above the LINAC are of concern since these areas contain passageways and a lounge area. These areas are currently classified as unrestricted areas[4] under the requirements of the *Code of Federal Regulations* [Ref. 4], since they show radiation exposure which would result in a personnel absorbed dose of less than (a) two millirem in any one hour, and (b) 100 millirem in any seven consecutive days.

On October 22, 1991, a radiation survey of neutron and gamma radiation was conducted, at a height of zero inches above the floor, while the LINAC was operating at electron energies of 90 MeV and a current of 0.12 microamps. It was again noted during this survey that the radiation levels being monitored were dependent on the tuning of the electron beam, i.e., a finely tuned beam produces less radiation in the areas under question. Figures 9 and 10 show the results of the neutron and gamma radiation surveys, respectively. It is apparent from Figure 10 that the radiation pattern from the electron injection system, the first accelerator section, and the ten foot lens does produce a noticeable effect on the radiation levels in the first floor of Halligan Hall, since this radiation pattern is generally conical.

[4] An unrestricted area means any area to which access is not controlled for purposes of protection of individuals from exposure to radiation and radiation materials.

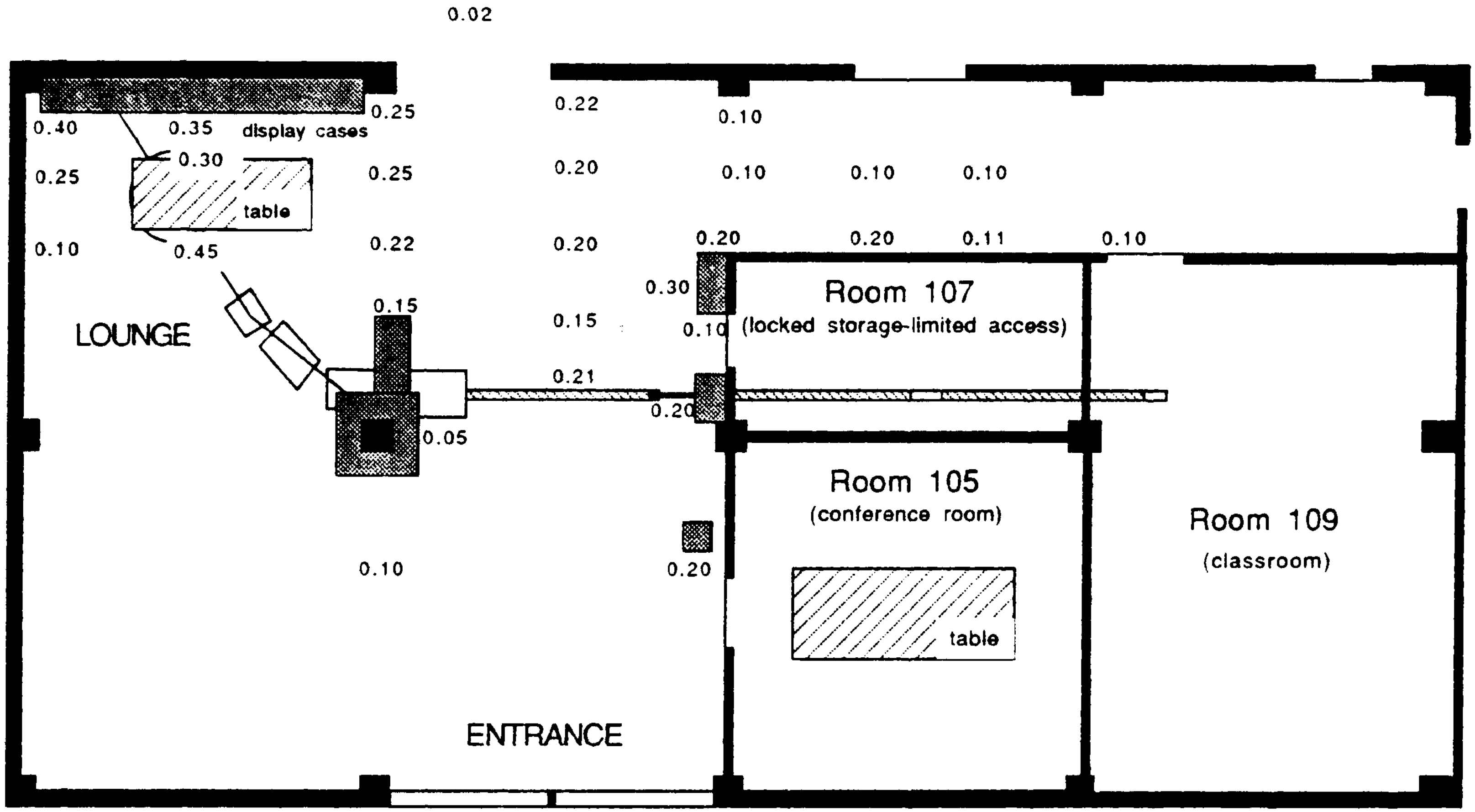

Figure 9: Halligan Hall (first floor) neutron radiation levels (mrem per hour).

Measurements taken while the LINAC was operating at 90 MeV with a current of 0.12 microamps. Note that the increased values in the upper left corner are above the beam dump point, a known source of radiation.

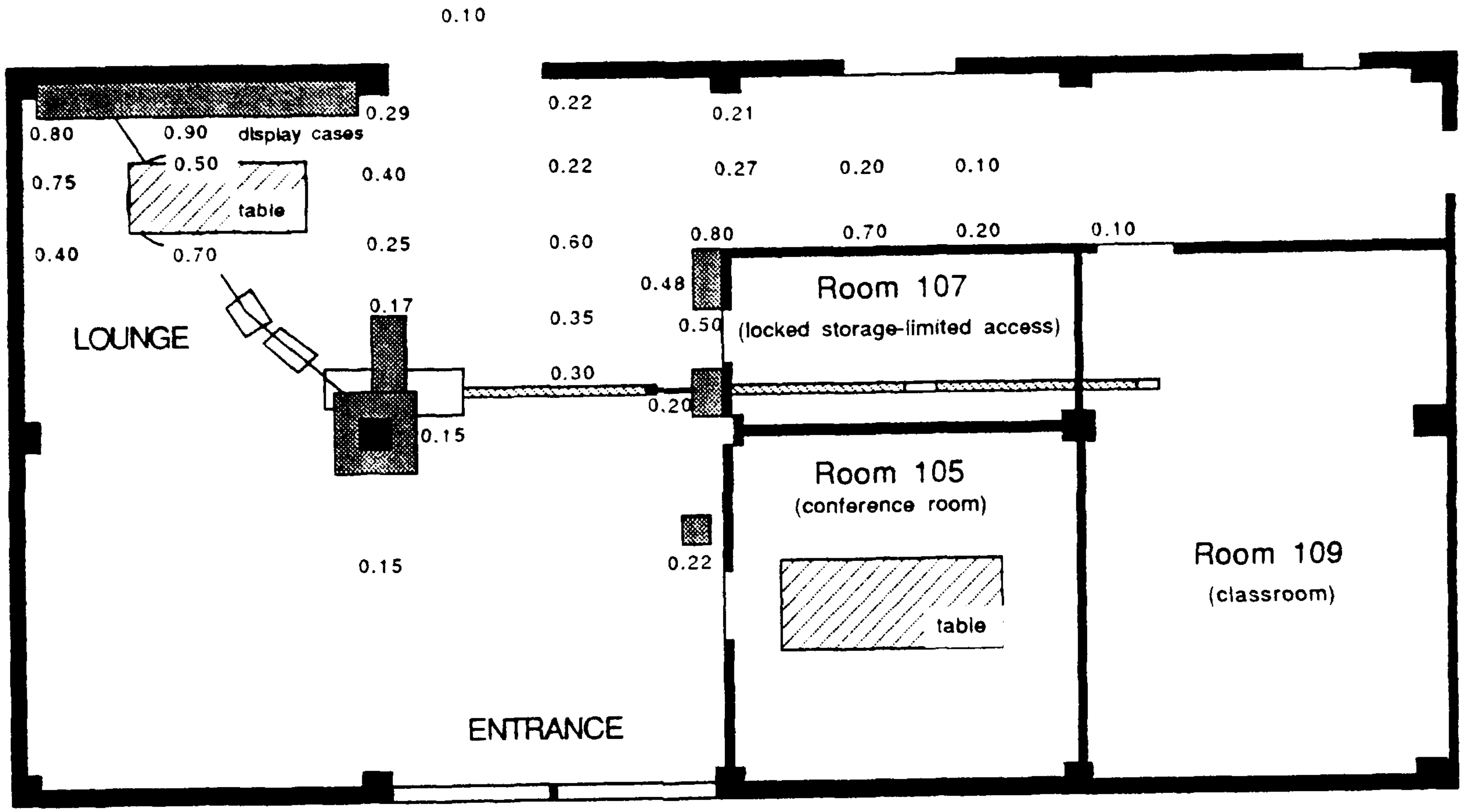

Figure 10: Halligan Hall (first floor) gamma radiation levels (mrem per hour).

Measurements taken while the LINAC was operating at 90 MeV with a current of 0.12 microamps. Note that the increased values around the upper left corner of room 107 are due to the scatter of radiation from the first accelerator section and the ten foot lens.

Figure 11 shows the total radiation levels, in millirem per hour, in the areas in question on the first floor of Halligan Hall. These radiation levels range in value from 0.12 to 1.25 millirem per hour, with the maximum values being located above the beam dump location. Nowhere do they exceed two millirem per hour. This means that this area should retain its unrestricted classification. These values are considered to be as low as reasonably achievable due to the high cost of installing additional radiation shielding along the LINAC tunnel roof. Display cases and bookcases have been placed in those areas with the highest radiation readings in order to make those spaces inaccessible.

D. COMPARISON WITH PREVIOUS STUDIES

In 1967 Soper conducted a radiation survey on the then newly completed LINAC. In 1985 Zurey conducted a radiation survey to verify the reduction in radiation levels following the installation of supplementary lead and borated paraffin shielding on the tunnel roof. Both of these surveys found that the highest levels of radiation are located in the beam optics area, endstation, and power supply area, although the klystrons are separately shielded.

Table 4 shows the survey levels determined by Soper and Zurey compared to readings taken recently. The values shown for the 1991/92 values represent the total (gamma plus neutron) radiation level as measured by an IM-231 B/PD radiac for the gamma level and an AN/PDR-70 radiac for the neutron level, recorded while the LINAC was operating at 90 MeV with a current of 0.12 microamps. The 1991/92 values are instantaneous readings that were taken manually after two minutes of radiac exposure.

During the two minute exposure time for survey locations B and C, the person taking the readings was located in the LINAC control room, and was only exposed to the radiation field long enough to read the radiac meters. During the two minute exposure time for the endstation measurement, however, the person was located just inside the access door. Since the access door measurement had been taken first, it was possible to estimate the dose (1.2 millirem) that would be received by the person if the measurement was made in this manner. A pocket dosimeter was used to provide warning if the radiation exposure rate became dangerously high. This pocket dosimeter indicated that the dose received during the measurement was zero. Minimal exposure was confirmed by the Radiation Exposure Report (NAVMED Form 6470/3) for the exposure period in question, which showed that the person who did the measurements received three millirem total for the full exposure period.

TABLE 4: SURVEYS OF LINAC RADIATION LEVELS

Site	1967 Readings (mrem/hr)	1985 Readings (mrem/hr)	1991/92 Readings (mrem/hr)
A. Endstation	100+	100+	107
B. Rear Door	50.0	45.0	80
C. Access Door	40.0	55.0	35
X. Control Room (maximum)	3.5	0.5	0.6
First Floor (maximum)	10.0	1.2	1.25

Note 1: These site locations are shown in Figure 12.

Note 2: 1967 and 1985 gamma readings are as measured by AN/PDR-27 radiacs while the 1991/92 readings are as measured by an IM-231 B/PD Eberline RO-2 radiac.

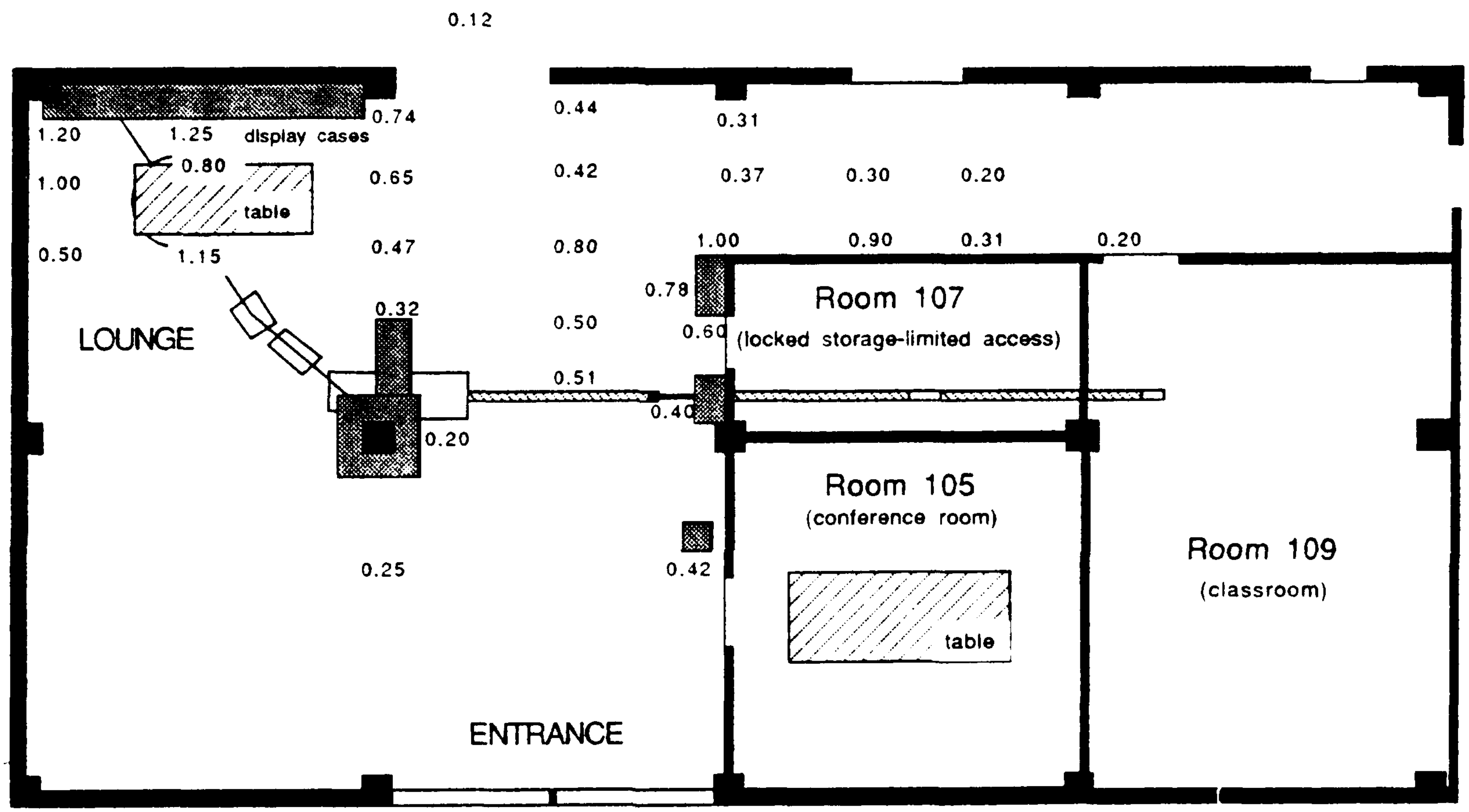

Figure 11: Halligan Hall (first floor) total radiation levels (mrem per hour).

Measurements taken while the LINAC was operating at 90 MeV with a current of 0.12 microamps. Note that the increased values around the upper left corner of room 107 show that the radiation pattern created by the first accelerator section and the ten foot lens is conical, as one expects given the cylindrical symmetry of the LINAC acceleration components.

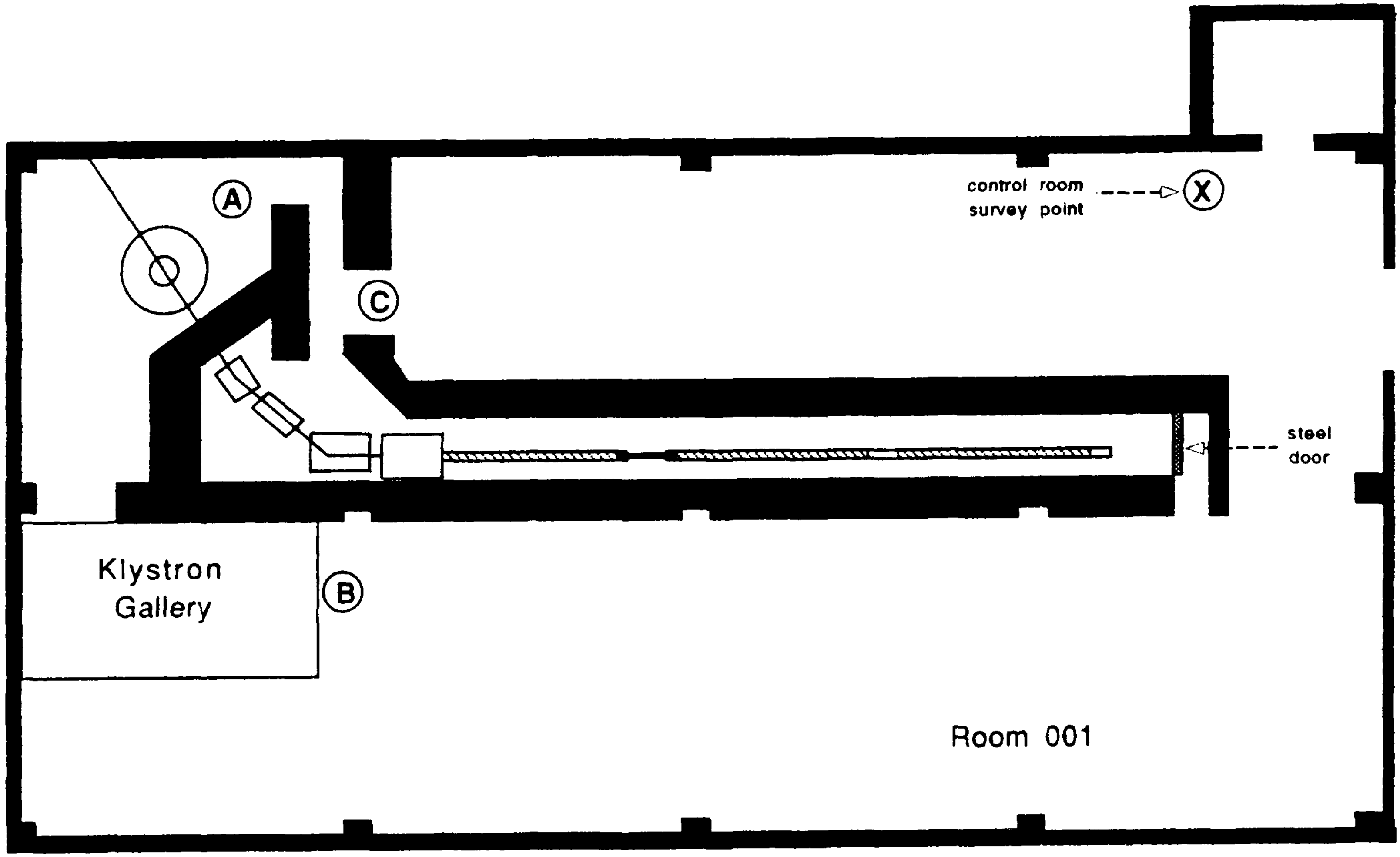

Figure 12: Position of comparison survey points in Halligan Hall basement.

E. SUPPLEMENTAL SHIELDING RECOMMENDATIONS

Supplemental shielding, in addition to that presently installed as shown in Figure 13, is recommended only for the side of the LINAC that is closest to the control room. No other supplemental shielding is recommended because radiation levels in sites other than the control room are considered to already be as low as reasonably achievable.

The first recommendation is to install additional lead, in the form of two by four by eight inch bricks, along the exterior side of the LINAC, as shown in Figure 14. Installation as shown will require 145 bricks. These bricks are available through the government supply system and their weight, 1.9 tons, will not exceed the floor's load limit [Ref. 2].

The ratio of the gamma radiation level obtained from survey location number 9 (where there is currently lead shielding installed) to that obtained from location number 10 (where there is a gap in the shielding) can be used to provide an estimate of the reduction that installation of this lead will effect. By this method, it is estimated that installation of these bricks will decrease the gamma radiation level in the control room by a factor of 1.4, or approximately 50 percent.

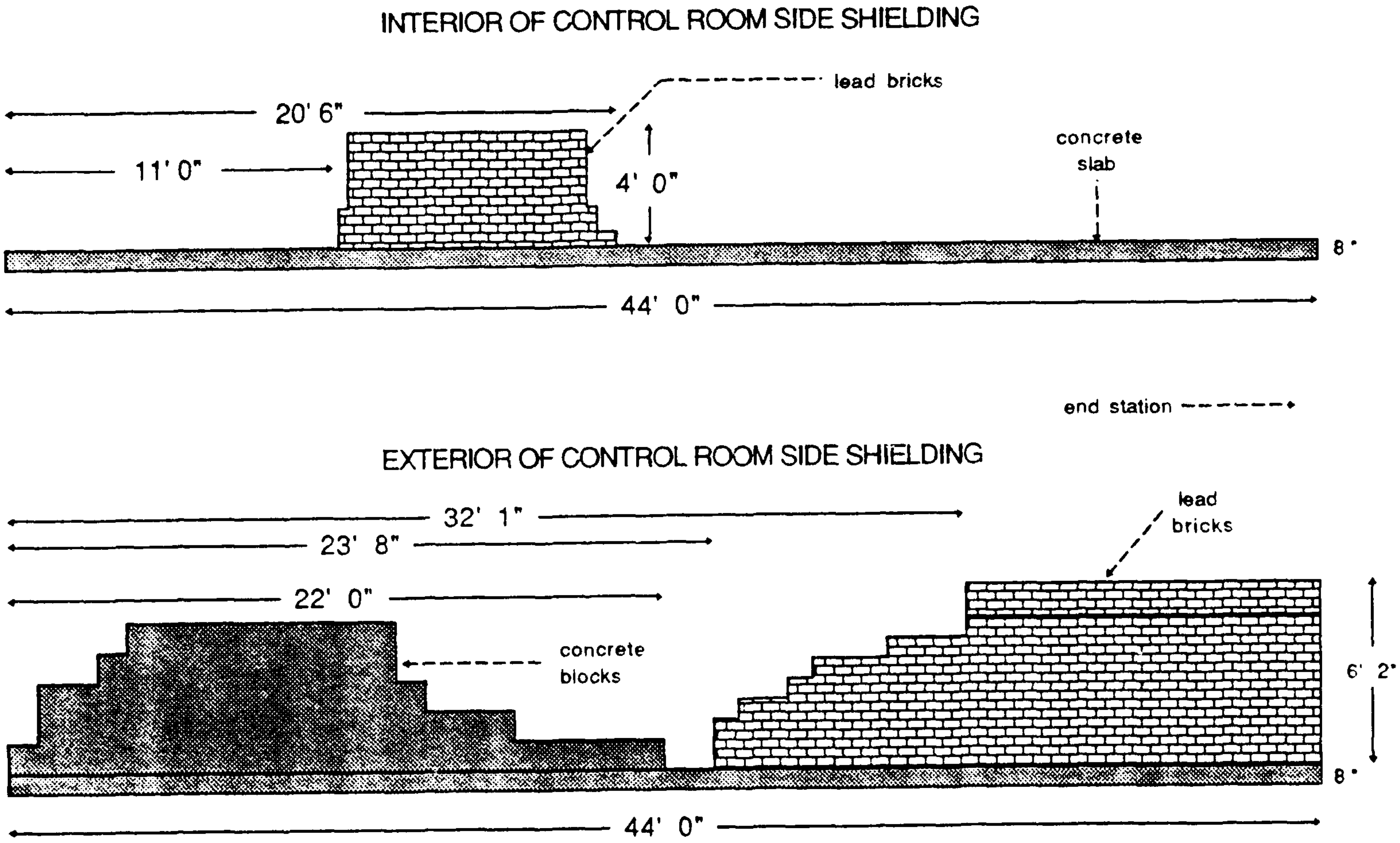

Figure 13: Installed supplemental shielding on control room side of LINAC.

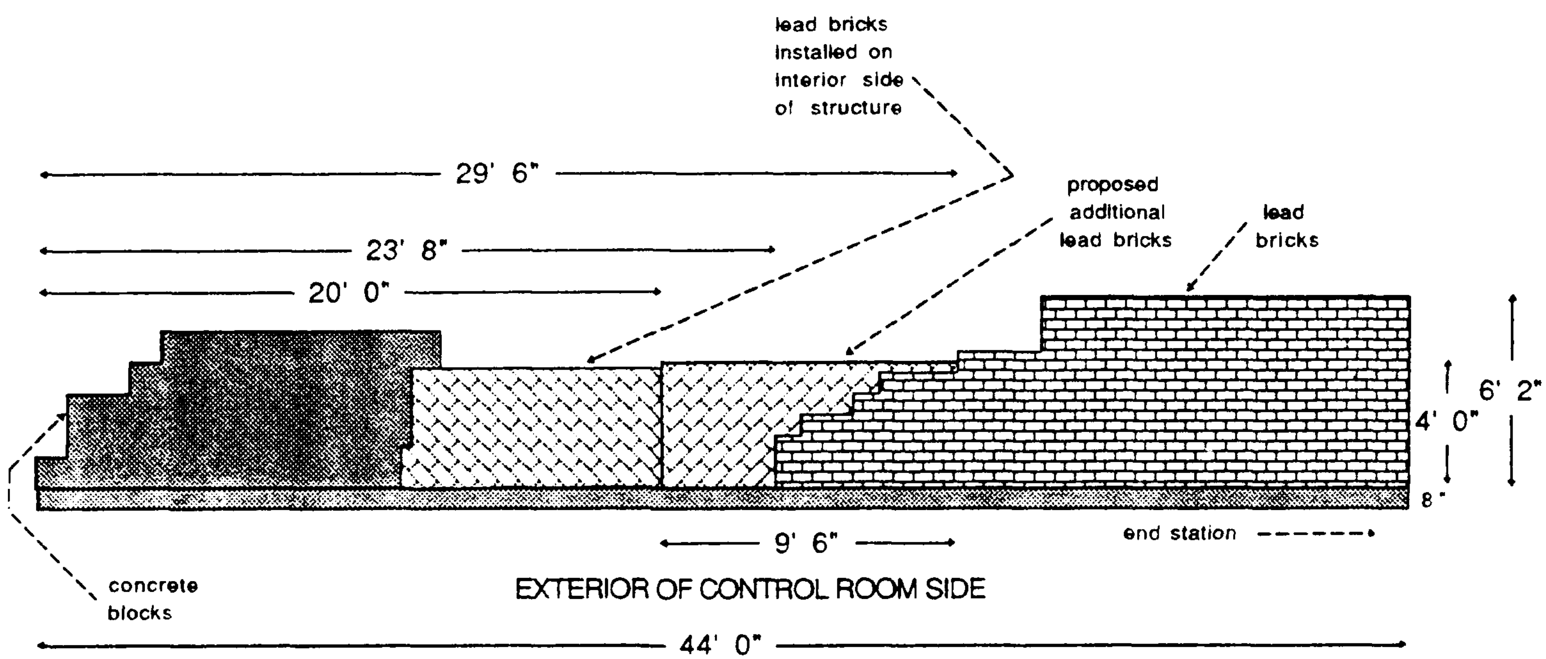

Figure 14: Proposed supplemental shielding on control room side of LINAC.
The installation of the additional lead bricks as shown will fill the existing gap and should reduce the gamma radiation level in the control room by a factor of 1.4. This reduction is due to the anticipated removal of the peak gamma radiation located about 28 feet from the front end of the LINAC.

The second recommendation is to install five percent boron-polyethylene in the form of four by four foot sheets, one inch thick, as shown in Figure 15. This will provide a neutron shield around the control room, as discussed in Professor Maruyama's Memoranda for the Record of 10 April 1989 [Ref. 5] and 7 April 1989 [Ref. 6], and will further reduce the gamma radiation level. Three sheets, available from Reactor Experiments, Inc. at a price of about $500.00 per sheet, resulting in a total cost of approximately $1500.00, will be needed to accomplish installation as shown in the figure. To reduce installation costs, it is recommended that these sheets be placed between the LINAC's side structure blocks and the concrete blocks that form the supplemental shielding at the forward end of the LINAC. The one sheet that is crosswise to the passageway should be mounted as a swinging door to allow easy access through the passageway during periods that the LINAC is not being operated.

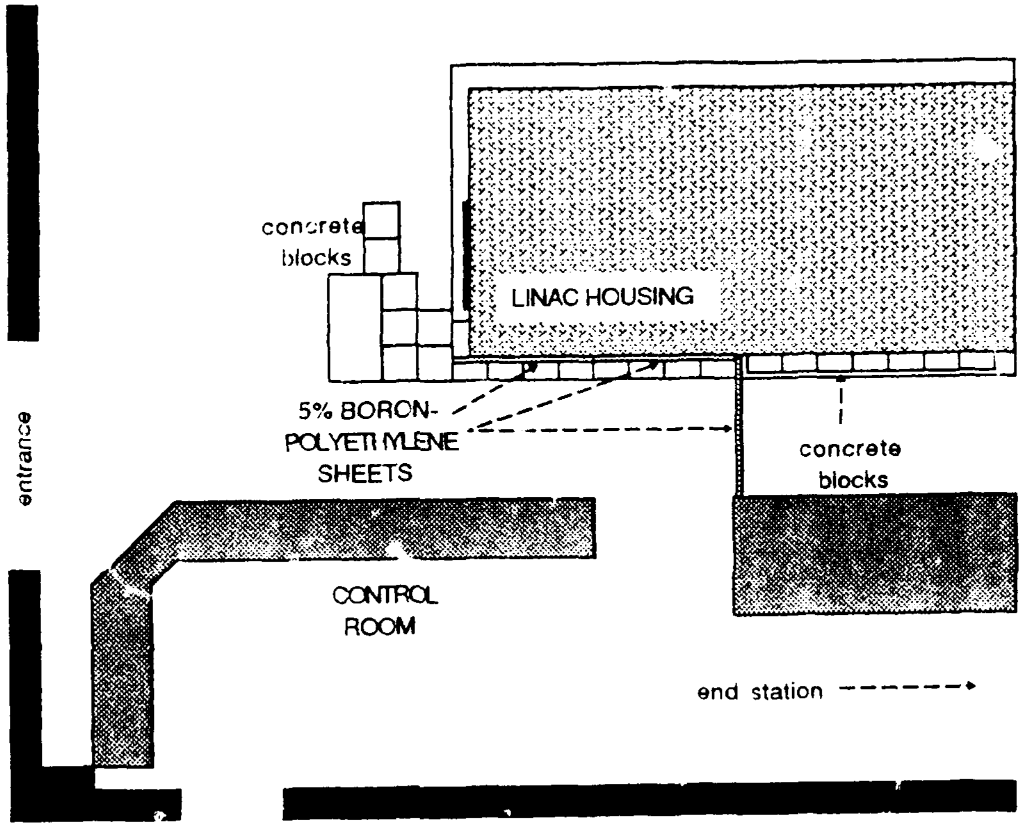

Figure 15: Recommended installation location of 5% boron-polyethylene shielding.

Installation of these three sheets will provide a neutron radiation shield between the LINAC control room and the primary sources of neutron radiation for that area.

III. DT-648/PD NEUTRON ENERGY CORRECTION FACTOR FOR NPS LINAC

The neutron response of the Navy's DT-648/PD (DT-648) thermoluminescent dosimeter is very dependent on the neutron energy spectrum to which it is exposed. To correct its energy dependency problem, a technique was developed which reliably predicts the over- or underresponse of the DT-648 to a wide range of neutron energies. This technique, although designed for long duration exposures, can, with only minor modifications, be used for a pulsed source such as the LINAC to generate a site-specific neutron energy spectra correction factor which is applied to personnel dosimeters.

A. RECENT EXPERIMENTS

Not knowing which electron energy and slit width combination produced the highest neutron radiation levels, measurements were taken for slit widths of 100 and 300, corresponding to energy spreads of 0.30% and 1.14% respectively, at electron energies of 30, 60, and 90 MeV. Measurements were taken using two AN/PDR-70 radiacs simultaneously to allow the readings to be compared without having to correct for LINAC operating parameter differences. Eighteen neutron measurements were taken for each electron energy and slit width combination: three with AN/PDR-70(#1) fully assembled (FA) and AN/PDR-70(#2) partially assembled

(PA), three with AN/PDR-70(#1) PA and AN/PDR-70(#2) FA, and the final three with both AN/PDR-70's disassembled (D). Raw data from these measurements are provided in Appendix G. Since the readings of the two radiacs are to be compared, the readings of radiac number two must be corrected as described in Appendix D. The corrected readings for AN/PDR-70(#2) are shown in Appendix H.

The technique for determining the thermoluminescent dosimeter neutron energy correction factor (TLD NECF), described in a letter from Naval Surface Warfare Center, results in the following statistically derived equation

$$\mathrm{NECF} = \left[0.024 + 0.087 \times \frac{\text{PA reading}}{\text{FA reading}}\right]^{-1} .$$

This equation is currently being used by the National Naval Medical Command to correct the DT-648 TLD's response to different neutron environments. [Ref. 7]

The TLD neutron energy correction factors obtained for each run are contained in Appendix I. The average values for each electron energy and slit width combination are shown in Table 5. Figure 16 shows these values graphically.

As can be readily seen from Figure 16, the NECF shows a dependence on the electron energy level through the neutron radiation field produced during LINAC operation, as expected. From these results (and since the LINAC normally operates at electron energies greater than 80 MeV at slit widths ranging from 100 to 300) the author's opinion is that the final TLD NECF should be the average of the values obtained at 90 MeV electron energy, or

$$NECF_{final} = 0.341 \pm 0.015 .$$

TABLE 5: AVERAGE TLD NEUTRON ENERGY CORRECTION FACTORS

Electron Energy (MeV)	Slit Width	Average NECF
30	300	0.398
30	100	0.403
60	300	0.348
60	100	0.358
90	300	0.332
90	100	0.350

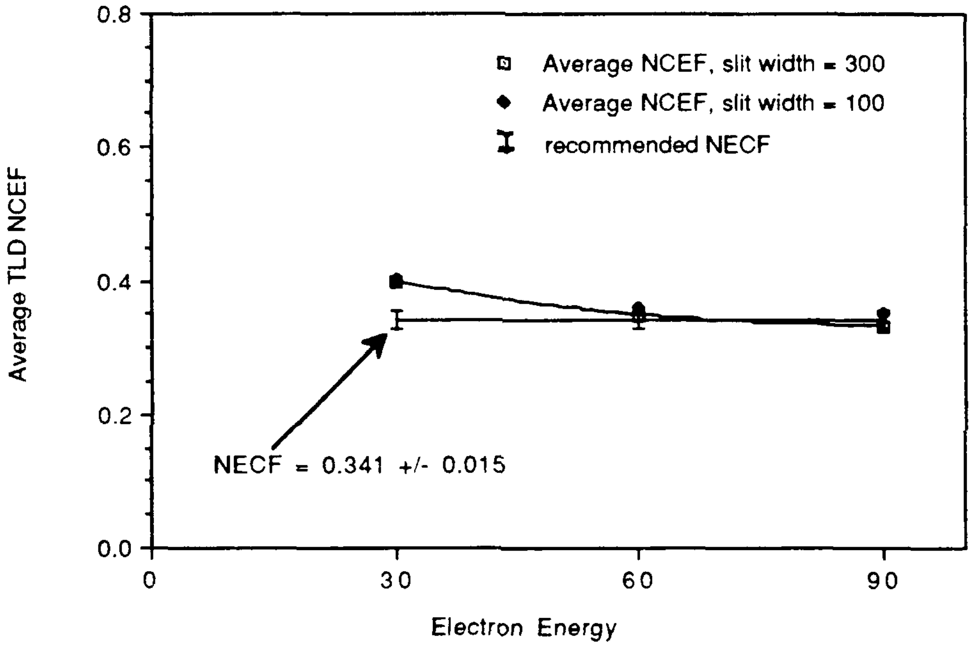

Figure 16: Average TLD NECF for electron energy and slit width combinations.

B. PREVIOUS EXPERIMENTS

On May 12, 1987, a determination of the TLD NECF for the DT-583 personnel dosimeter was conducted. Data were obtained from seven locations around the LINAC, as shown in Figure 17, with the electron energy level greater than 90 MeV and at an unknown current. Since only one AN/PDR-70 (serial number unknown) radiac was utilized in these measurements, and the duration of the exposure was only 20 seconds, the results obtained are suspected to contain large errors. Table 6 shows the results of analyzing this data using the procedure of Section III.A.

Averaging the TLD NECFs obtained in the seven locations yields a final TLD NECF of 3.56, an order of magnitude higher than that found in this work. It is believed that this difference is due to the short exposure time and that the partially assembled and fully assembled measurements were not taken simultaneously, thereby allowing variations in the LINAC operating parameters to affect the results. Other factors to be considered are the change in the neutron radiation energy spectrum due to increased shielding and natural degradation of the linear accelerator over the four year period between the surveys. For the above reasons, plus the extensiveness of the recent surveys, confidence lies with the new work.

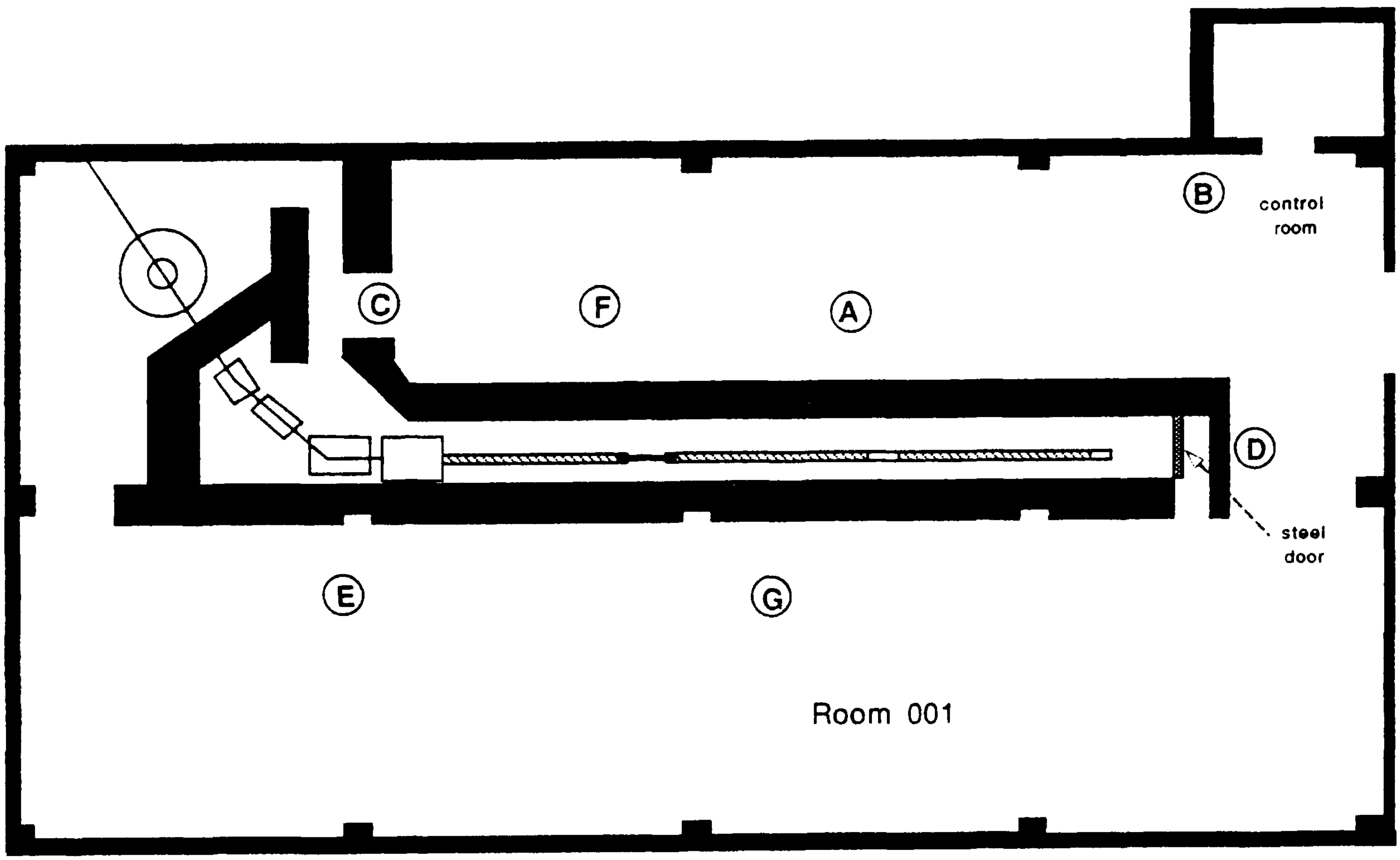

Figure 17: Site locations of 1987 neutron survey.

TABLE 6: ANALYSIS OF PREVIOUS NEUTRON SURVEY DATA

Site No.	PA Radiac Reading (Counts)	FA Radiac Reading (Counts)	PA/FA	TLD NECF
A	654	199	3.29	3.23
B	727	185	3.93	2.73
C	5449	1845	2.95	3.56
D	340	116	2.93	3.58
E	26575	9149	2.90	3.61
F	1920	662	2.90	3.62
G	1947	875	2.23	4.60

Note: The current study indicates that these previous measurements may be in error due to the short exposure time of the AN/PDR-70 instrumentation to the radiation field.

C. SECONDARY METHOD FOR DETERMINATION OF TLD NEUTRON ENERGY CORRECTION FACTOR

A separate method of determining the TLD NECF involves the exposure readings of the TLDs.[5] When a TLD is placed on the front of the area monitor, the neutron exposure reading obtained from the area monitor divided by the neutron exposure reading obtained from the TLD should be equal to the dosimeter neutron energy correction value. The same is true if the TLD is strapped to a plexiglass block (to act as a reflector for fast neutrons). Results from this method are shown in Table 7 for the LINAC control room and in Table 8 for the first floor of Halligan Hall. Since personnel wearing TLDs spend most of their time in the LINAC control room, the presently used

[5] This method is currently being evaluated by the Naval Research Laboratory to obtain parameters for establishing neutron energy correction factors for the TLD.

method, discussed in Section III.A above, indicates an over-estimate of the neutron dose evaluation. Although the data for this method do not contain enough signal to justify conclusive decisions about a neutron energy correction factor for the linear accelerator, they indicate that either the value obtained in Section III.A is valid or that the statistically derived formula being used by the National Naval Medical Command is incorrect. At any rate, both methods indicate a lower TLD NECF is necessary than the default value of 5.2 that is currently being used.

TABLE 7: RESULTS OF SECONDARY DETERMINATION OF TLD NECF FOR LINAC CONTROL ROOM

Exposure Period	AM #350 Neutron Exposure Reading (mrem)	AM #350A Neutron Exposure Reading (mrem)	Area Block Neutron Exposure Reading (mrem)	Ratio of AM #350 to AM #350A	Ratio of AM #350 to Area Block
3 Jul 91-15 Aug 91	6	31	44	0.19	0.14
30 Sep 91-18 Nov 91	0	7	7	0.00	0.00
18 Nov 91-2 Jan 92	2	7	12	0.29	0.17
2 Jan 92-21 Feb 92	0	0	0	indefinite	indefinite
21 Feb 92-9 Apr 92	0	0	0	indefinite	indefinite

TABLE 8: RESULTS OF SECONDARY DETERMINATION OF TLD NECF FOR FIRST FLOOR HALLIGAN HALL

Exposure Period	AM #349 Neutron Exposure Reading (mrem)	AM #349A Neutron Exposure Reading (mrem)	Ratio of AM #349 to AM #349A
3 Jul 91- 15 Aug 91	7	11	0.64
30 Sep 91- 18 Nov 91	0	0	indefinite
18 Nov 91- 2 Jan 92	2	0	indefinite
2 Jan 92- 21 Feb 92	0	0	indefinite
21 Feb 92- 9 Apr 92	2	0	indefinite

IV. CONCLUSIONS

The primary conclusion of this thesis is that the radiation levels produced by the linear accelerator are not high enough to be cause for alarm, if the proper personnel safety precautions are followed. In fact, the radiation levels in the first floor of Halligan Hall, above the LINAC, do not justify the cost of installing additional shielding.

The neutron energy correction factor that should be assigned to the NPS LINAC is 0.34. When one considers that the default NECF is 5.2, this represents a reduction in the TLD measured neutron dose evaluation by a factor of 15. To appreciate this reduction, consider the highest neutron personnel dose evaluation since July 3, 1991: 38 millirem. If the NECF determined by this thesis is applied, that neutron dose evaluation would be reduced to three millirem for that exposure period.

Even more significant is that, applying this NECF to the last six radiation exposure reports, from July 3, 1991 to April 9, 1992, only 12 of the 117 TLD monitored neutron dose evaluations would have been greater than one millirem per exposure period. Of these, only six represent a neutron dose evaluation of two or three millirem per exposure period. This, coupled with the estimated dose reduction due to the installation of additional neutron shielding, shows that neutron radiation monitoring by thermoluminescent dosimeters is not required and should be discontinued.

The views of the Officer in Charge of the Naval Dosimetry Center concerning the reduction of the neutron energy correction factor that is currently assigned to the Naval Postgraduate School's linear accelerator are reproduced as Appendix J.

APPENDIX A: LINAC DESCRIPTION

The Naval Postgraduate School's LINAC is a travelling wave type accelerator. Electromagnetic waves capture the 80 keV injected electrons and accelerate them to up to 100 MeV. The accelerator is composed of three major subsystems described below. For a more detailed description of the LINAC, see Barnett and Cunneen [Ref. 8]. (Operating characteristics of the LINAC are shown in Table A1.)

A. ACCELERATOR SUBSYSTEM

The accelerator subsystem consists of the electron injector, three ten foot waveguides (accelerator sections), and the associated support systems. Each of the three waveguides is powered by a Klystron amplifier which delivers up to 21 megawatts of peak power.

B. BEAM OPTICS SUBSYSTEM

The purpose of the beam optics subsystem is to provide a well-defined beam to the target. To remove the instrumentation from the path of the forward radiation produced during electron acceleration, deflection of the beam, accomplished by two deflection magnets, is required. Mechanical energy-defining slits are utilized to tailor the spread in electron energies to experimental requirements. Two quadropole magnets are used to provide beam steering.

C. MONITORING SUBSYSTEM

The beam monitoring, beam utilization, and beam disposal processes all occur in the endstation of the LINAC. Radiation shielding for this area is provided by cement walls and ceiling.

TABLE A1: LINAC OPERATING CHARACTERISTICS

Maximum Beam Energy	100 MeV
Pulse Frequency	60 pulses per second
Maximum Pulse Length	2 microseconds
Klystron Peak Power	21 megawatts
Klystron Frequency	2.856 gigahertz

APPENDIX B: BASIC PRINCIPLES

This appendix is designed to provide general introductory material. It may be skipped without loss of continuity. The material contained in this appendix can be found in most introductory references about radiation and radiation detectors, but is mainly derived from four sources. Section A's primary sources are Tsoulfanidis [Ref. 9] and Knoll [Ref. 10], while the primary sources for Section B are Cooper [Ref. 11] and the U.S. Army Chemical Center and School [Ref. 12].

A. RADIATION

Until about 1900, the word *radiation* was used to describe electromagnetic waves. Around the turn of the century, electrons, x-rays and natural radioactivity were discovered and were included in the term radiation. Today, radiation refers to the whole electromagnetic spectrum as well as to emitted forms of all the atomic and subatomic particles that have been discovered.

Radiation can be grouped into two types, depending on their energy: nonionizing and ionizing. Nonionizing radiation is electromagnetic radiation with a wavelength of 1.0 nm or longer that does not have the minimum energy required to produce ionization in typical materials, either by direct interaction or by the secondary products of its interaction. Ionizing radiation includes the rest of the electromagnetic spectrum and atomic and subatomic particles with energy greater than this minimum.

The three types of radiation that are observed externally during LINAC operation, and thus are of concern to this thesis, are beta radiation, gamma radiation, and neutrons. Each of these is categorized as ionizing radiation and presents its own specific potential hazards to the health of personnel.

1. Beta Radiation

Beta radiation consists of very high energy electrons which usually have been ejected from a disintegrating nucleus. These beta particles have a relative ionizing power of 100.[6] Each beta particle can possess an energy from within a wide spectrum; therefore, the interaction of one beta particle with matter may be different from the interaction of a second beta particle with the same matter.

When a beta particle moves through matter, its electric field interacts with the fields from orbital electrons and can push them out of their orbits, thus ionizing the atom. Since the rest mass of the beta particle is equal to the mass of the orbital electrons, large deflections in the beta particle's trajectory can occur in single interactions. A deviation in the beta particle's path, when caused by radial acceleration, such as described above, results in bremsstrahlung radiation, which further ionizes the surrounding medium.

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[6] The relative ionizing power of a type of radiation is a measure of the number of ionizations it will produce compared to the number produced by gamma radiation under identical conditions. A gamma ray's relative ionizing power is set equal to one.

2. Gamma Radiation

Gamma radiation is the emission of high energy photons by an excited nucleus as it undergoes transitions towards stability. Ionization of matter by gamma radiation can occur in three ways: (1) photoelectric effect; (2) Compton effect; and (3) pair production.

a. Photoelectric Effect

In the photoelectric effect a photon strikes an orbital electron and knocks the electron out of its position in the atom. All of the energy of the incident photon is used in removing the electron and in giving the electron kinetic energy (the photon is absorbed). The freed electron behaves as a beta particle and can cause secondary ionizations. This method of gamma absorption is predominant for gamma photons of relatively low energy.

b. Compton Effect

In Compton scattering the incident gamma photon is deflected, by an interaction with an electron, from its original direction. The photon transfers a portion of its energy to the electron and, therefore, has a different frequency after the interaction. Since all angles of scattering are possible, the electron may recoil with an energy that can vary from zero to a large fraction of the gamma ray's energy. This effect is usually the predominant mechanism of interaction for gamma ray energies typical of radioisotope sources.

c. *Pair Production*

When the energy of the incident gamma photon is greater than 1.02 MeV, electron-positron pair production is possible. Pair production can occur when a gamma ray passes close to the nucleus of an atom. The gamma ray can be converted into two particles: an electron and a positron. The total cross section for pair production is very nearly proportional to the square of the charge of the nucleus (Z^2), so that the effect is much more important in heavy materials than in light ones. All of the energy of the incident photon is converted to the mass of the two particles (explaining the minimum energy requirement) plus their kinetic energy. Ionization of the medium is done by the electron and positron. This method of gamma radiation absorption becomes predominant for high energy gamma photons.

3. Neutron Radiation

Neutron radiation consists of neutrons ejected from an excited or fissioning nucleus. Since neutrons are uncharged they interact with matter via short range nuclear forces (the strong interaction). Neutron interaction with matter is very energy dependent and also varies with different materials. Neutrons do not directly cause ionization of the medium because they are not charged particles; they do cause indirect ionization of the medium by several processes.

a. Nucleus Removal

Although not usual, neutrons are capable of striking the nucleus of a small atom (such as hydrogen) and knocking the nucleus free of its orbital electrons. The resultant positively charged particle could cause considerable ionization in the medium, depending on its energy.

b. Neutron Capture With Gamma Photon Emission

A neutron may be captured by a nucleus, with the instantaneous emission of a gamma photon. The gamma photon ionizes the material as described in Section B.A.2.

c. Neutron Capture to Form New Isotope

The neutron may be captured by the nucleus of an atom to form a new isotope of that atom. This new isotope is generally radioactive and will emit alpha, beta, or gamma radiation, which will ionize the medium.

B. RADIATION DETECTION AND MEASUREMENT

Since nuclear radiation cannot be detected by any of the human senses, it is essential to utilize radiation, detection, identification, and computation (radiac) instruments. These instruments measure radiation indirectly; that is, by the detection and measurement of some phenomenon that is produced by the radiation. As a result of ionization and the effects of radiation on matter, there are five general types of phenomena which can be used to measure nuclear radiation.

1. **Photographic**

When ionizing radiations strike the chemical emulsion of a photographic film, chemical changes similar to the effects of ordinary light occur. Thus the variation in quantity of ionizing radiation results in different degrees of exposure of the film. This effect provides a very reliable method (commonly called photodosimetry) for detecting and measuring radiation.

2. **Colorimetric**

Numerous liquids and crystals exhibit a color change when exposed to radiation. Some show a continuous change of color whose extent is proportional to the amount of radiation to which the material was exposed. Others, especially certain dye solutions, show an abrupt change of color after a specific amount of ionization has taken place. The composition of these liquids can be changed so that a different amount of radiation is required to produce the color change.

3. **Luminescence**

Certain materials have the property of emitting tiny flashes of light, or scintillations, when struck by ionizing radiation. One device that uses this phenomenon to measure radiation is a scintillation counter. A scintillating crystal is mounted on a special electron tube (photomultiplier) to produce small flashes of light. The photomultiplier has several metal-coated surfaces arranged so that the scintillations from the crystal cause electrons to break away from the first of these surfaces. Each of these electrons will in turn dislodge several more electrons from the second surface, and so on, until a measurable electrical pulse is produced. Since the wavelength of the light emitted by the crystal is proportional to the energy of the ionizing radiation, this provides a means for detecting and measuring radiation.

4. Electrical Collection of Ions

Ionization is the production of charged particles (ions) by the removal of electrons from atoms. This removal of an electron from a neutral atom forms two oppositely charged particles called an electron-ion pair. When an electric field is established in an ionized gas, the positive ions will move towards the cathode and the negative ions will move towards the anode. When the ion strikes the electrode (either the anode or the cathode) it will be neutralized, thus reducing the charge on the electrode and causing a net current flow. This current is a measure of the absorbed radiation.

5. Semiconductor

When PN junction materials are exposed to radiation, their internal structures are changed, and the current through the junction is increased in proportion to the incident dose rate. This phenomenon makes it possible to calibrate an ammeter to indicate any dose rate.

C. GAS-FILLED DETECTORS

A radiation detector that is based on the collection of ions will usually have its two electrodes in a coaxial configuration, with the gas-filled sensitive volume being the space between the electrodes, as shown in Figure B1. The electric field in that volume provides forces that separate the ion pairs, making it possible to operate the device as a radiation detector. The primary source for the information in this section is the U.S. Army Facilities Engineer Support Agency [Ref. 13].

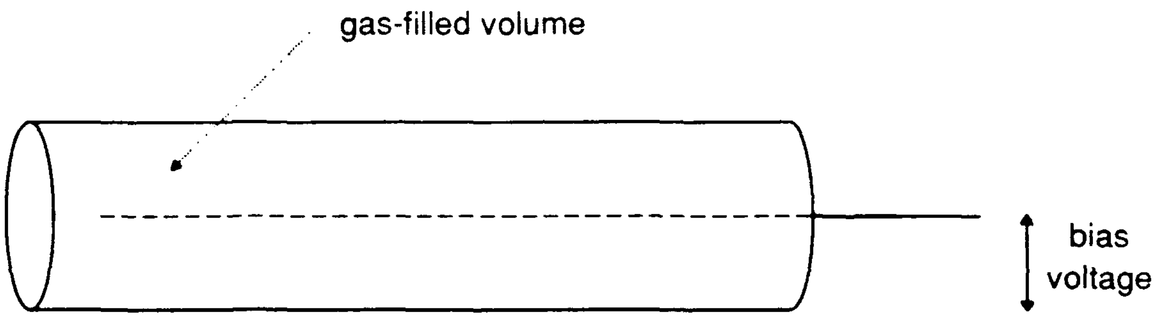

Figure B1: Coaxial detector.

1. Detector Efficiency

There are several inherent factors which decrease the efficiency of a gas-filled detector. One of these, geometric efficiency, is due to the actual physical size of the detector probe. If the detector completely surrounded the source, it could collect all of the radiation emitted by the source. But, since this is not practical in most applications, a small probe detector is used, thus reducing its efficiency.

Another factor which affects detection efficiency is the construction of the probe walls. Many probes are constructed entirely out of metal which makes the detector insensitive to radiation with a low penetration probability, such as alpha and beta radiation and low energy x-rays. Detectors designed to detect these types of radiation must have one end of the probe enclosed with only a thin film of mylar or other material which allows a large fraction of these types of radiations to enter the probe interior. Once inside, however, they have a high probability of being detected because of their high probability of interaction with matter. Thus, virtually all of the alphas and betas which enter the probe are detected.

On the other hand, radiation with a high penetration potential, such as gamma radiation which passes freely through the probe's wall, often will pass completely through the probe without interacting and thus will not be detected. Therefore only a small fraction of the gamma radiation will be detected.

2. Pulse Height Determination

Gas-filled radiation detectors can be operated in pulse mode, where each individual quantum of radiation which happens to interact in the detector produces an electrical pulse whose amplitude (pulse height) is directly proportional to the corresponding charge generated within the detector. The pulse height may vary over a wide range depending on the type of detector under consideration and is a function of the detector's applied voltage. A plot of pulse height versus applied voltage, as shown in Figure B2, shows six well-defined voltage regions.

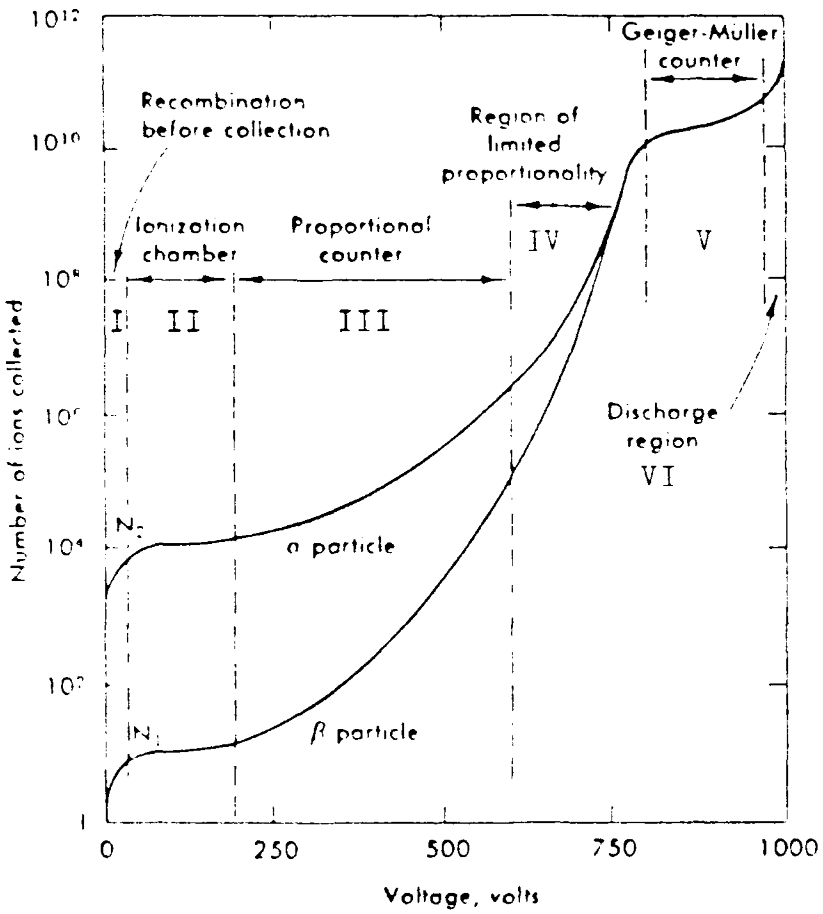

Figure B2: Pulse height versus applied voltage. [Ref.14] No gas-filled detectors are designed to operate in regions I, IV, and VI. The IM-231 B/PD ion chamber is an example of a radiac designed to operate in region II,while the AN/PDR-70 operates in region III and the AN/PDR-27 operates in region V. The primary differences in the radiacs are in its sensitivity and in its ruggedness.

a. *Region I -- Recombination*

In this region, the electrostatic force due to the applied voltage is opposed by the atom's recombination force.[7] As the applied voltage is increased, fewer ions recombine and a stronger pulse is generated.

b. *Region II -- Ion chamber*

In this region the applied voltage is increased to the point that virtually all of the ions strike the electrodes and recombination is negligible. In this range the pulse height is a function of the radiation intensity only (i.e., as the radiation intensity increases, so does the pulse height).

There are several advantages in using an ion chamber detector. The first is that the applied voltage may vary without affecting the resulting signal output. Another advantage is that the ion chamber has a flat energy response. Only at very low energies (less than approximately 50 keV) will the device underrespond due to the attenuation of low energy radiation by the probe walls. The third advantage is the ion chamber has no dead time.[8]

The disadvantages of the ion chamber are that it is not very sensitive or rugged. Small pulses can look like intrinsic circuit

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[7] Recombination occurs when an ion pair recombines before either ion strikes an electrode.

[8] Dead time is the time interval necessary for the detector to recover from one response and be ready for the next ionization event.

noise even in the best detectors. This low signal strength requires the use of sensitive amplifiers which are relatively delicate.

The IM-231 B/PD Eberline RO-2 used in the radiation surveys documented by this thesis is an example of an ion chamber detector.

c. Region III -- Proportional

In this region, the applied voltage has been increased to the point that the ions are pulled apart with such force that they cause secondary ionizations as they proceed to their respective electrodes. This phenomenon is known as gas multiplication. As the voltage is increased even further, the ions formed by the secondary ionization events can cause tertiary ionization events which can result in a cascade of ions in the vicinity of the initial event. This cascade of ions paralyzes that portion of the electrode where it occurs and causes a dead time of approximately 0.5 microseconds at that part of the electrode. Despite this localized dead time, a high count rate is still possible with a proportional detector.

The advantages of this type of detector are that it is very sensitive, especially to low energy beta radiation and x-rays, and that its output signal voltage is high enough that it does not require a delicate, sensitive amplifier like the ion chamber does. The disadvantages of the proportional detector are that it requires a stable power supply (since its output depends on the applied voltage) and that its localized dead time can result in some loss of accuracy.

The AN/PDR-70 used in the radiation surveys documented by this thesis is an example of a proportional detection instrument. This device is made sensitive to neutrons by coating the inside of the probe with boron. Neutrons interact with boron-10 to produce lithium-7 and alpha particles. This interaction is detected by the instrument because of the numerous ionization events caused by the alpha particles.

d. Region IV -- Limited Proportionality

As the applied voltage is increased even further, the gas multiplication factor increases to the point where it is no longer independent of the number of initial ions produced (large for small pulses and small for large pulses). This means that the pulse height may not be proportional the number of initial ion pairs, and, therefore, the ability to distinguish between different pulse heights is lost. Since accurate information cannot be obtained in this region, no gas-filled detectors are designed to operate as limited proportional counters.

e. Region V -- Geiger-Mueller (G-M)

Increasing the applied voltage even further continues to increase the gas multiplication factor to the point where a single ion pair will cause the entire probe to avalanche. This causes a dead time in the detector of approximately 300 microseconds which substantially reduces its count rate capability, or time resolution.

Most G-M counters are filled with argon gas, which is easily ionized and thus increases the detector's sensitivity. When the positive argon ions reach the cathode and are neutralized, ultraviolet light is emitted which reacts with the surrounding material and, by way of the photoelectric effect, produces more electrons. These electrons will interact with the neutral argon atom, causing more positive argon ions and, therefore, more ultraviolet light and so forth so that the probe is continually saturated with a succession of avalanches.

Ethyl alcohol or halogens such as chlorine or bromine are used as quenching gases to dampen this effect. As the positive argon ions migrate towards the cathode, they chemically react with the quenching gas molecules and transfer their energy so only positively charged quenching gas ions actually reach the cathode. These gas ions do not produce ultraviolet light when neutralized, so the detector stabilizes and is ready for the next ionization event in a shorter time span. However, when ethyl alcohol molecules are neutralized, they break up and are thus gradually exhausted. Halogen quenchers are not depleted when neutralized, so this type of detector has a much longer life.

A major disadvantage of the G-M counter is that it is very energy dependent at low and high energy levels. It has a flat response only from approximately 100 keV to 10 MeV. The G-M tube will underrespond at very low energies because of attenuation by the probe's walls. It overresponds upwards of five times the actual count rate at low energies because of the greater probability of photon interaction with matter via the photoelectric effect. This same overresponse is seen at very high energies due to pair production.

Another disadvantage of the G-M tube is its long dead time. This precludes its use with x-ray machines because the initial portion of the x-ray pulse triggers the avalanche, and the remainder of the pulse is missed during the subsequent dead time. Thus there is no information provided regarding the height or duration of each x-ray pulse. This is also true in a pulsed type radiation source, such as the LINAC. The detector's readings, while operating in the radiation fields of these types of sources, must be verified by an ion chamber detector (which does not have this limitation) in order to be considered valid .

The AN/PDR-27 G-M detector used in the radiation surveys documented by this thesis is an example of a radiation detection instrument designed to operate in the Geiger-Mueller region.

f. Region VI -- Avalanche

In this region, the applied voltage is so high that electrons are spontaneously removed from the neutral atoms resulting in a continuous discharge of the probe which will cause burnout. No gas-filled radiation detectors are intentionally operated in this region.

D. THERMOLUMINESCENT DOSIMETER (TLD)

The material in this section is primarily derived from Knoll [Ref. 10].

When the inorganic crystals known as thermoluminescent dosimeters are exposed to ionizing radiation, an electron is elevated to the conduction band from the valence band and a positive hole is formed within the crystal structure. Instead of promoting the quick recombination of electron-hole pairs, as in scintillation crystals, materials are used which exhibit high concentrations of trapping centers within the band gap. The desired process is now one in which electrons are elevated from the valence to the conduction band by the incident radiation, but are then captured at one of the trapping centers. If the distance of the trap energy level below the conduction band is sufficiently large, there is only a small probability per unit time at room temperatures that the electron will escape the trap by being thermally excited back to the conduction band. Therefore, exposure of the material to a continuous source of radiation, although not resulting in a significant yield of prompt scintillation light, leads to the progressive buildup of trapped electrons.

The positive holes are trapped in an analogous process. Both the electron and the hole are then locked in place unless additional thermal energy is given to the crystal. A sample of the TLD material will therefore function as an integrating detector in which the number of trapped electrons and holes is a measure of the radiation exposure.

After the exposure period, the TLD sample is heated so that the electrons or holes can acquire enough thermal energy to overcome the trap and recombine. This will result in the emission of a visible photon (the basis of the TLD signal) if the energy level of the trap is about three or four electron volts. If, ideally, one photon is emitted for each trapped electron, the total number of emitted photons can be used as a measure of the number of electron-hole pairs created by the radiation.

The photon yield can then be recorded as a function of the TLD's temperature in a "glow curve". The basic signal related to the radiation exposure is the total number of emitted photons, or the area under the glow curve. Raising the TLD sample to a relatively high temperature will deplete all of the traps and effectively erase the exposure record. TLDs therefore have the advantage of being reusable.

Lithium flouride (LiF) TLDs have the best suitability for long-term exposure because of their almost negligible fading (electrons or holes escaping the traps and recombining) at room temperature and their low average atomic number, which does not differ greatly from that of tissue or air. The energy deposited in LiF is therefore closely correlated with the gamma ray exposure over a wide range of gamma ray energy (0.01 to 1000 rads). At higher doses, the LiF material displays a nonlinear increase in response per unit exposure, which makes it dependent on photon energy in the photoelectric region.

Because of the content of 7.4 percent Li-6 in natural lithium, the TLD is sensitive to slow neutrons through the $(n,{}^{4}He)$ reaction. The DT-648/PD thermoluminescent dosimeter (DT-648), used by LINAC workers, uses a LiF-600 chip to capture neutrons that are thermalized by the wearer's body. However, the sensitivity of the DT-648 is very energy dependent and this affects the response of the dosimeter when it is exposed to a neutron energy spectrum (field) that is significantly different from the one in which it was calibrated. To correct its energy dependency problem, a technique was developed, by the Naval Research Laboratory, the Naval Surface Warfare Center, and the Naval Dosimetry Center, which reliably predicts the over or under response of the DT-648 to a wide range of neutron energies.[9]

[9] This technique is discussed in more detail in Chapter III.

APPENDIX C: STANDARD DOSE LIMITS

OCCUPATIONAL EXPOSURE	
Quarterly Limit (whole body)	1.25 rem
GENERAL PUBLIC EXPOSURE	
Hourly Limit	less than 2 millirem
Daily Limit	less than 100 millirem in any seven consecutive days

Note: Data compiled from the *Code of Federal Regulations.* [Ref. 15]

APPENDIX D: SURVEY SPECIFICATION AND INSTRUMENTATION

A. SURVEY POINT SELECTION

Since the LINAC Control Area is the only space normally occupied during LINAC operation, it became the only logical site for the majority of the radiation measurements. A detector height of 32 inches was chosen, as it is the average height at which a dosimeter badge is worn (typically, 24 inches sitting and 40 inches standing). Figure 4 shows the location of the survey points on the LINAC's floor plan.

B. RADIATION MEASUREMENT DEVICES

Six primary radiation detection and measurement devices were utilized in this experiment. Specific information on each radiac is:

- Radiac No.1: AN/PDR-70 serial number C-140 with electronics package serial number C-140. Calibration date: 23 Jan 91. Scale setting: x10.
- Radiac No. 2: AN/PDR-70 serial number A-67 with electronics package serial number A-67. Calibration date: 23 Jan 91. Scale setting: x10.
- Radiac No. 3: AN/PDR-27 serial number C-277. Calibration date: 17 Apr 91. Scale setting: 0.5.
- Radiac No. 4: AN/PDR-27 serial number B-313. Calibration date: 24 Jan 91. Scale setting: 0.5.
- Radiac No. 5: RO-2 serial number 4947. Calibration date: 22 Apr 91. Scale setting: 5.
- Radiac No. 6: RO-2 serial number 5011. Calibration date: 22 Apr 91. Scale setting: 5.

The first potential problem is that the two AN/PDR-27 and AN/PDR-70 radiacs would not give the same measurement under identical situations. Since the LINAC is not a continuous source, the radiation levels change with each operation as well as with each configuration change. In order to compare the data from one configuration with another, or to compare the data from two operations utilizing the same configuration, the measurements must be normalized. This normalization requires that the radiacs have essentially the same response. Figures D1 and D2 show the results of the comparison tests of the AN/PDR-27 and the AN/PDR-70 radiacs, respectively. As can be readily seen from Figure D1, the two AN/PDR-27 radiacs' responses are within five percent of each other. This accuracy is considered to be well within the experimental requirements. Figure D2, however, shows that one of the AN/PDR-70 radiacs (Serial Number C-140) continuously read an average of 11.1 percent less than the other one when both radiacs were exposed to the same field while in the disassembled (D), partially assembled (PA), and fully assembled (FA) configurations. This discrepancy must be accounted for in any comparison of the readings of the two AN/PDR-70 radiacs.

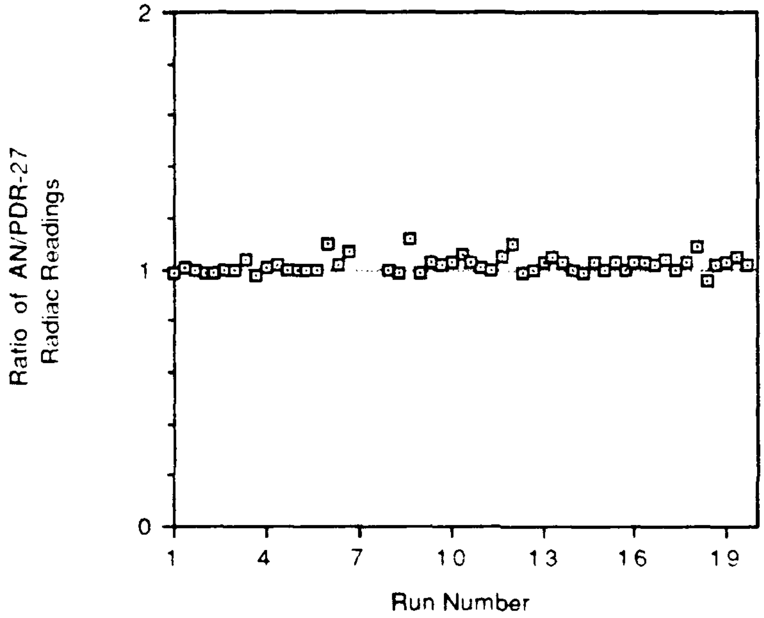

Figure D1: AN/PDR-27 comparison test.

There are no data points on this graph for run number seven because counters were not available at the time of that run. The range of the readings used in this ratio test is on the order of 0.3 millirem per hour. This graph is the ratio of radiac number three to radiac number four.

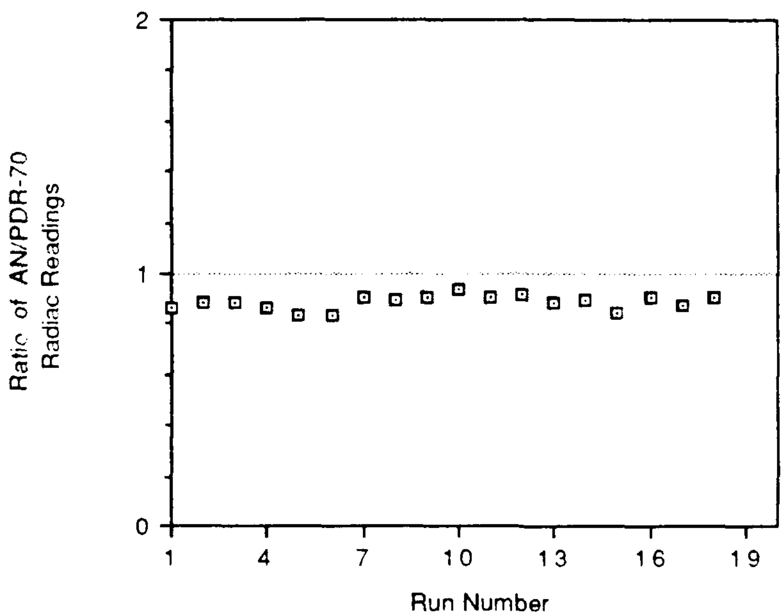

Figure D2: AN/PDR-70 comparison test.

The range of readings used in this ratio test is on the order of five millirem per hour. This graph is the ratio of radiac number one to radiac number two, and shows the 11.1% average difference in the two radiac's readings.

The RO-2 radiacs were used to determine the accuracy of the AN/PDR-27 measurement of X-ray exposure rates, due to the known exposure limitations of the AN/PDR-27. As Figure D3 shows, the ratio of the average of the two AN/PDR-27 values for that run to the average of the two RO-2 values for that run is on the order of unity, therefore showing that the AN/PDR-27 radiacs were not saturated by the radiation produced during LINAC operation, even though the LINAC is a pulsed source and the AN/PDR-27 is a Geiger-Mueller counter.

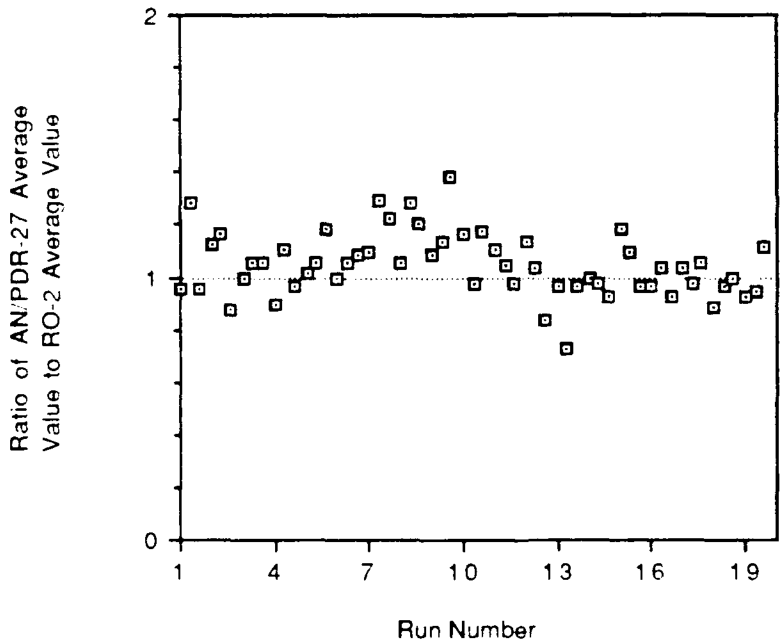

Figure D3: AN/PDR-27 to RO-2 ratio test.
This graph shows that the AN/PDR-27 radiacs were not saturated during the measurements. The range of readings used in this comparison is on the order of 0.2 millirem per hour.

C. AN/PDR-70 RATIO CORRECTION

As discussed in Section D.B above, comparison of the values of the two AN/PDR-70 radiacs requires a correction term. Table D1 provides a summary of the ratio value for the two AN/PDR-70 radiacs for the runs where the two radiacs were in the same configuration, i.e., both radiacs were in the disassembled state. The ratio values in Table D1 are all the ratio of radiac number one to radiac number two, where the radiac numbers correspond to the numbers in Section D.B above. The average ratio value for the electron energy and slit width combination is the correction term that will be applied to the obtained measurement of radiac number two for all of the other runs that have the same electron energy and slit width combination. For example, the measurements obtained from radiac number two in runs one (a,b,c) and two (a,b,c) will be multiplied by the ratio correction term of 0.88 to convert these measurements to the same normalization as radiac number one for the same runs.

TABLE D1: AN/PDR-70 RATIO CORRECTION TERMS

Run No.	Energy (MeV)	Slit Width	Run A Ratio Value	Run B Ratio Value	Run C Ratio Value	Average Ratio Value
3	30	300	0.87	0.89	0.89	0.88
6	30	100	0.87	0.83	0.83	0.84
9	60	300	0.91	0.90	0.91	0.91
12	60	100	0.94	0.91	0.92	0.92
15	90	300	0.89	0.90	0.85	0.88
18	90	100	0.91	0.88	0.91	0.90

APPENDIX E: CONTROL ROOM GAMMA RADIATION LEVELS

Tables E1 through E6 show the results of measurements of the gamma radiation level in the LINAC control room. In these tables the radiac number specified refers to the radiac with the same number in Appendix D, Paragraph B. The values for average gamma, counts per minute (CPM) and counts per click (CPC), were obtained by averaging the readings of radiac numbers two and three, after dividing these values by the total time (in minutes) for CPM or by the total number of clicks indicated by the SEM for CPC.

TABLE E1: GAMMA RADIATION LEVELS FOR 30 MeV ELECTRONS AT A SLIT WIDTH OF 300

Run No.	Radiac # 3 (mrem per hour per micro-amp)	Radiac # 4 (mrem per hour per micro-amp)	Radiac # 5 (mrem per hour per micro-amp)	Radiac # 6 (mrem per hour per micro-amp)	Radiac # 7 (mrem per hour per micro-amp)	Average Gamma (CPM per micro-amp)	Average Gamma (CPC per micro-amp)	Average Gamma (mrem per hour per micro-amp)
1A	3.12	3.24	3.60	3.00	3.00	14201	531.18	3.19
1B	3.00	3.12	2.40	2.40	2.76	14472	536.94	2.74
1C	2.88	2.88	3.00	3.00	2.40	13349	536.04	2.83
2A	3.96	4.08	3.60	3.60	3.60	16356	613.44	3.77
2B	3.00	3.24	2.40	3.00	3.00	15365	559.32	2.93
2C	3.48	3.36	3.60	4.20	3.00	15867	554.58	3.53
3A	1.20	1.20	1.20	1.20	1.20	5573	161.10	1.20
3B	1.32	1.20	1.20	1.20	1.20	5740	176.52	1.22
3C	1.20	1.32	1.20	1.20	1.20	5631	190.92	1.22

TABLE E2: GAMMA RADIATION LEVELS FOR 30 MeV ELECTRONS AT A SLIT WIDTH OF 100

Run No.	Radiac # 3 (mrem per hour per micro-amp)	Radiac # 4 (mrem per hour per micro-amp)	Radiac # 5 (mrem per hour per micro-amp)	Radiac # 6 (mrem per hour per micro-amp)	Radiac # 7 (mrem per hour per micro-amp)	Average Gamma (CPM per micro-amp)	Average Gamma (CPC per micro-amp)	Average Gamma (mrem per hour per micro-amp)
4A	3.24	3.24	3.60	3.60	3.00	16386	770.16	3.34
4B	3.24	3.36	3.00	3.00	3.36	16954	589.20	3.19
4C	4.32	4.44	4.20	4.80	3.60	18343	676.86	4.27
5A	4.44	4.68	4.20	4.80	4.80	18235	533.40	4.58
5B	3.96	4.20	3.60	4.20	3.36	17554	782.10	3.86
5C	3.96	3.84	3.00	3.60	3.60	15991	726.00	3.60
6A	0.72	0.80	0.72	0.80	0.88	3860	119.88	0.78
6B	0.88	0.76	0.76	0.80	0.88	4028	119.26	0.82
6C	0.88	0.84	0.80	0.80	0.80	4234	151.40	0.82

TABLE E3: GAMMA RADIATION 'LEVELS FOR 60 MeV ELECTRONS AT A SLIT WIDTH OF 300

Run No.	Radiac # 3 (mrem per hour per micro-amp)	Radiac # 4 (mrem per hour per micro-amp)	Radiac # 5 (mrem per hour per micro-amp)	Radiac # 6 (mrem per hour per micro-amp)	Radiac # 7 (mrem per hour per micro-amp)	Average Gamma (CPM per micro-amp)	Average Gamma (CPC per micro-amp)	Average Gamma (mrem per hour per micro-amp)
7A	1.44	1.44	1.20	1.44	1.20	unknown	unknown	1.34
7B	1.44	1.34	0.96	1.20	1.20	unknown	unknown	1.23
7C	1.63	1.30	0.96	1.44	1.44	unknown	unknown	1.35
8A	0.96	1.06	0.96	0.96	0.72	5225	106.87	0.93
8B	1.20	1.25	0.96	0.96	0.96	5388	104.02	1.07
8C	1.20	1.10	0.96	0.96	0.96	5515	112.51	1.04
9A	0.80	0.92	0.80	0.80	0.72	4172	94.52	0.81
9B	0.92	0.88	0.80	0.80	0.80	4339	177.06	0.84
9C	1.08	1.12	0.80	0.80	0.88	4567	195.50	0.94
19A	0.72	0.76	0.80	0.80	0.80	3734	147.34	0.78
19B	0.76	0.72	0.80	0.76	0.72	3404	118.24	0.75
19C	0.80	0.88	0.72	0.80	0.80	3668	126.18	0.80

TABLE E4: GAMMA RADIATION LEVELS FOR 60 MeV ELECTRONS AT A SLIT WIDTH OF 100

Run No.	Radiac # 3 (mrem per hour per micro-amp)	Radiac # 4 (mrem per hour per micro-amp)	Radiac # 5 (mrem per hour per micro-amp)	Radiac # 6 (mrem per hour per micro-amp)	Radiac # 7 (mrem per hour per micro-amp)	Average Gamma (CPM per micro-amp)	Average Gamma (CPC per micro-amp)	Average Gamma (mrem per hour per micro-amp)
10A	0.56	0.60	0.40	0.60	0.60	2835	144.88	0.55
10B	0.80	0.76	0.80	0.80	0.60	3069.	84.42	0.75
10C	0.80	0.84	0.80	0.60	0.60	3467	243.26	0.73
11A	0.88	0.88	0.80	0.80	0.60	3595	250.46	0.79
11B	1.04	1.04	0.80	1.20	0.68	4802	405.08	0.95
11C	0.72	0.84	0.80	0.80	0.80	4613	212.00	0.79
12A	2.76	2.64	2.40	2.40	2.40	11030	286.26	2.52
12B	2.52	2.40	2.40	2.40	2.16	11114.	259.56	2.38
12C	2.64	2.40	3.60	2.40	2.40	11581	283.80	2.69

TABLE E5: GAMMA RADIATION LEVELS FOR 90 MeV ELECTRONS AT A SLIT WIDTH OF 300

Run No.	Radiac # 3 (mrem per hour per micro-amp)	Radiac # 4 (mrem per hour per micro-amp)	Radiac # 5 (mrem per hour per micro-amp)	Radiac # 6 (mrem per hour per micro-amp)	Radiac # 7 (mrem per hour per micro-amp)	Average Gamma (CPM per micro-amp)	Average Gamma (CPC per micro-amp)	Average Gamma (mrem per hour per micro-amp)
13A	0.96	0.90	1.02	0.90	0.90	4200.99	190.95	0.94
13B	0.84	0.90	1.20	1.20	1.08	4269.18	112.95	1.04
13C	0.84	0.90	0.90	0.90	0.96	3908.49	98.70	0.90
14A	1.26	1.26	1.20	1.32	1.20	5857.32	126.54	1.25
14B	1.20	1.26	1.20	1.32	1.08	4760.19	134.49	1.21
14C	1.08	1.14	1.20	1.20	1.20	4546.50	112.98	1.16
15A	1.26	1.08	0.90	1.08	0.90	4354.50	86.52	1.04
15B	1.14	1.02	0.90	1.08	1.08	3781.11	91.14	1.04
15C	1.02	1.08	1.08	1.08	1.02	4511.34	95.43	1.06

TABLE E6: GAMMA RADIATION LEVELS FOR 90 MeV ELECTRONS AT A SLIT WIDTH OF 100

Run No.	Radiac # 3 (mrem per hour per micro-amp)	Radiac # 4 (mrem per hour per micro-amp)	Radiac # 5 (mrem per hour per micro-amp)	Radiac # 6 (mrem per hour per micro-amp)	Radiac # 7 (mrem per hour per micro-amp)	Average Gamma (CPM per micro-amp)	Average Gamma (CPC per micro-amp)	Average Gamma (mrem per hour per micro-amp)
16A	0.84	0.90	0.90	0.90	0.96	4431	90.84	0.90
16B	1.14	1.08	1.08	1.08	1.08	5173	111.51	1.09
16C	1.08	1.14	1.20	1.20	1.20	5095	112.38	1.16
17A	1.02	0.96	0.96	0.96	0.90	4982	102.42	0.96
17B	1.14	1.20	1.20	1.20	1.20	5462	117.21	1.19
17C	1.26	1.26	1.20	1.20	1.20	5762	126.51	1.22
18A	1.02	0.90	1.08	1.08	1.20	4643	91.74	1.06
18B	1.08	1.14	1.08	1.20	0.96	4681	94.83	1.09
18C	1.08	1.20	1.08	1.20	0.96	4648	93.21	1.10

APPENDIX F: CONTROL ROOM NEUTRON RADIATION LEVELS

Tables F1 through F6 show the results of measurements of the gamma radiation level in the LINAC control room. In these tables the radiac number specified refers to the radiac with the same number in Appendix D, Section B. The ratio correction term is described in Appendix D, Section C and its value is derived in Table D1.

TABLE F1: NEUTRON RADIATION LEVELS FOR 30 MeV ELECTRONS AT A SLIT WIDTH OF 300

Run No.	Radiac No.	Radiac Reading (mrem per hour)	Ratio Correction Factor	Corrected Reading (mrem per hour)	Corrected Reading (mrem per hour per microamp)
1A	1	0.50	1.00	0.50	6.00
1B	1	0.50	1.00	0.50	6.00
1C	1	0.45	1.00	0.45	5.40
2A	2	1.00	0.88	0.88	10.56
2B	2	0.95	0.88	0.84	10.03
2C	2	0.95	0.88	0.84	10.03

TABLE F2: NEUTRON RADIATION LEVELS FOR 30 MeV ELECTRONS AT A SLIT WIDTH OF 100

Run No.	Radiac No.	Radiac Reading (mrem per hour)	Ratio Correction Factor	Corrected Reading (mrem per hour)	Corrected Reading (mrem per hour per microamp)
4A	1	0.55	1.00	0.55	6.60
4B	1	0.60	1.00	0.60	7.20
4C	1	0.90	1.00	0.90	10.80
5A	2	1.00	0.84	0.84	10.08
5B	2	1.00	0.84	0.84	10.08
5C	2	1.00	0.84	0.84	10.08

TABLE F3: NEUTRON RADIATION LEVELS FOR 60 MeV ELECTRONS AT A SLIT WIDTH OF 300

Run No.	Radiac No.	Radiac Reading (mrem per hour)	Ratio Correction Factor	Corrected Reading (mrem per hour)	Corrected Reading (mrem per hour per microamp)
7A	1	0.50	1.00	0.50	2.40
7B	1	0.50	1.00	0.50	2.40
7C	1	0.50	1.00	0.50	2.40
8A	2	0.60	0.91	0.55	2.62
8B	2	0.50	0.91	0.46	2.18
8C	2	0.40	0.91	0.36	1.75
19A	1	0.25	1.00	0.25	1.00
19B	1	0.35	1.00	0.35	1.40
19C	1	0.40	1.00	0.40	1.60

TABLE F4: NEUTRON RADIATION LEVELS FOR 60 MeV ELECTRONS AT A SLIT WIDTH OF 100

Run No.	Radiac No.	Radiac Reading (mrem per hour)	Ratio Correction Factor	Corrected Reading (mrem per hour)	Corrected Reading (mrem per hour per microamp)
10A	1	0.10	1.00	0.10	0.40
10B	1	0.20	1.00	0.20	0.80
10C	1	0.20	1.00	0.20	0.80
11A	2	0.40	0.92	0.37	1.47
11B	2	0.50	0.92	0.46	1.84
11C	2	0.50	0.92	0.46	1.84

TABLE F5: NEUTRON RADIATION LEVELS FOR 90 MeV ELECTRONS AT A SLIT WIDTH OF 300

Run No.	Radiac No.	Radiac Reading (mrem per hour)	Ratio Correction Factor	Corrected Reading (mrem per hour)	Corrected Reading (mrem per hour per microamp)
13A	1	0.50	1.00	0.50	3.00
13B	1	0.25	1.00	0.25	1.50
13C	1	0.50	1.00	0.50	3.00
14A	2	0.50	0.88	0.44	2.64
14B	2	0.60	0.88	0.53	3.17
14C	2	0.50	0.88	0.44	2.64

TABLE F6: NEUTRON RADIATION LEVELS FOR 90 MeV ELECTRONS AT A SLIT WIDTH OF 100

Run No.	Radiac No.	Radiac Reading (mrem per hour)	Ratio Correction Factor	Corrected Reading (mrem per hour)	Corrected Reading (mrem per hour per microamp)
16A	1	0.40	1.00	0.40	2.40
16B	1	0.40	1.00	0.40	2.40
16C	1	0.50	1.00	0.50	3.00
17A	2	0.50	0.90	0.45	2.70
17B	2	0.60	0.90	0.54	3.24
17C	2	0.50	0.90	0.45	2.70

APPENDIX G: CONTROL ROOM SURVEY RAW DATA

This appendix contains the raw data obtained during the control room survey.

Definition of terms and abbreviations:

- Clicks = integrated current on electron beam current monitor (arbitrary units)
- Minutes = duration of measurement
- cpm = counts per minute (varies because of current instability)
- cpc = counts per click (proportional to counts per integrated charge)
- mrem per hr = reading on instrument face (instantaneous reading that varies during duration of measurement)
- Radiac Status = assembly configuration of radiac
  - FA = fully assembled
  - PA = partially assembled (detector tube covered with the internal polyethylene sleeves)
  - D = disassembled (detector tube only)

Run No.	Date Complete	Current (micro-amps)	Energy (MeV)	Slit Width	Radiac No.	Radiac Status	Counts	Clicks	Minutes	CPM per microamp	CPC per microamp	mrem per hour	mrem per hour per microamp
1A	6-May-91	0.08	30	300	1	FA	427	200	7.48	685.03	25.62	0.50	6.00
1A	6-May-91	0.08	30	300	2	PA	12240	200	7.48	19636.36	734.40	13.50	162.00
1A	6-May-91	0.08	30	300	3	FA	8768	200	7.48	14066.31	526.08	0.26	3.12
1A	6-May-91	0.08	30	300	4	FA	8937	200	7.48	14337.43	536.22	0.27	3.24
1B	6-May-91	0.08	30	300	1	FA	449	200	7.42	726.15	26.94	0.50	6.00
1B	6-May-91	0.08	30	300	2	PA	12247	200	7.42	19806.47	734.82	14.00	168.00
1B	6-May-91	0.08	30	300	3	FA	8994	200	7.42	14545.55	539.64	0.25	3.00
1B	6-May-91	0.08	30	300	4	FA	8904	200	7.42	14400.00	534.24	0.26	3.12
1C	6-May-91	0.08	30	300	1	FA	465	200	8.03	694.89	27.90	0.45	5.40
1C	6-May-91	0.08	30	300	2	PA	12506	200	8.03	18688.92	750.36	14.00	168.00
1C	6-May-91	0.08	30	300	3	FA	8937	200	8.03	13355.42	536.22	0.24	2.88
1C	6-May-91	0.08	30	300	4	FA	8930	200	8.03	13344.96	535.80	0.24	2.88
2A	6-May-91	0.08	30	300	1	PA	13174	200	7.50	21078.40	790.44	20.00	240.00
2A	6-May-91	0.08	30	300	2	FA	428	200	7.50	684.80	25.68	1.00	12.00
2A	6-May-91	0.08	30	300	3	FA	10131	200	7.50	16209.60	607.86	0.33	3.96
2A	6-May-91	0.08	30	300	4	FA	10315	200	7.50	16504.00	618.90	0.34	4.08
2B	6-May-91	0.08	30	300	1	PA	11582	200	7.28	19091.21	694.92	16.00	192.00
2B	6-May-91	0.08	30	300	2	FA	371	200	7.28	611.54	22.26	0.95	11.40
2B	6-May-91	0.08	30	300	3	FA	9229	200	7.28	15212.64	553.74	0.25	3.00
2B	6-May-91	0.08	30	300	4	FA	9414	200	7.28	15517.58	564.84	0.27	3.24
2C	6-May-91	0.08	30	300	1	PA	11625	200	6.99	19957.08	697.50	19.50	234.00
2C	6-May-91	0.08	30	300	2	FA	393	200	6.99	674.68	23.58	0.95	11.40
2C	6-May-91	0.08	30	300	3	FA	9243	200	6.99	15867.81	554.58	0.29	3.48
2C	6-May-91	0.08	30	300	4	FA	9242	200	6.99	15866.09	554.52	0.28	3.36
3A	13-May-91	0.17	30	300	1	D	6299	200	5.78	6538.75	188.97	10.50	63.00
3A	13-May-91	0.17	30	300	2	D	7247	200	5.78	7522.84	217.41	10.50	63.00
3A	13-May-91	0.17	30	300	3	FA	5358	200	5.78	5561.94	160.74	0.20	1.20
3A	13-May-91	0.17	30	300	4	FA	5381	200	5.78	5585.81	161.43	0.20	1.20

Run No.	Date Complete	Current (micro-amps)	Energy (MeV)	Slit Width	Radiac No.	Radiac Status	Counts	Clicks	Minutes	CPM per microamp	CPC per microamp	mrem per hour	mrem per hour per microamp
3B	13-May-91	0.17	30	300	1	D	6833	200	6.15	6666.34	204.99	12.00	72.00
3B	13-May-91	0.17	30	300	2	D	7707	200	6.15	7519.02	231.21	12.00	72.00
3B	13-May-91	0.17	30	300	3	FA	5994	200	6.15	5847.80	179.82	0.22	1.32
3B	13-May-91	0.17	30	300	4	FA	5771	200	6.15	5630.24	173.13	0.20	1.20
3C	13-May-91	0.17	30	300	1	D	7632	200	6.78	6753.98	228.96	12.00	72.00
3C	13-May-91	0.17	30	300	2	D	8588	200	6.78	7600.00	257.64	11.50	69.00
3C	13-May-91	0.17	30	300	3	FA	6266	200	6.78	5545.13	187.98	0.20	1.20
3C	13-May-91	0.17	30	300	4	FA	6461	200	6.78	5717.70	193.83	0.22	1.32
4A	6-May-91	0.08	30	100	1	FA	642	200	9.40	819.57	38.52	0.55	6.60
4A	6-May-91	0.08	30	100	2	PA	17703	200	9.40	22599.57	1062.18	16.00	192.00
4A	6-May-91	0.08	30	100	3	FA	12880	200	9.40	16442.55	772.80	0.27	3.24
4A	6-May-91	0.08	30	100	4	FA	12792	200	9.40	16330.21	767.52	0.27	3.24
4B	6-May-91	0.08	30	100	1	FA	479	200	6.97	824.68	28.74	0.60	7.20
4B	6-May-91	0.08	30	100	2	PA	13421	200	6.97	23106.46	805.26	16.00	192.00
4B	6-May-91	0.08	30	100	3	FA	9935	200	6.97	17104.73	596.10	0.27	3.24
4B	6-May-91	0.08	30	100	4	FA	9704	200	6.97	16707.03	582.24	0.28	3.36
4C	6-May-91	0.08	30	100	1	FA	569	200	7.38	925.20	34.14	0.90	10.80
4C	6-May-91	0.08	30	100	2	PA	15961	200	7.38	25952.85	957.66	18.50	222.00
4C	6-May-91	0.08	30	100	3	FA	11156	200	7.38	18139.84	669.36	0.36	4.32
4C	6-May-91	0.08	30	100	4	FA	11406	200	7.38	18546.34	684.36	0.37	4.44
5A	6-May-91	0.08	30	100	1	PA	11198	200	5.85	22970.26	671.88	22.00	264.00
5A	6-May-91	0.08	30	100	2	FA	385	200	5.85	789.74	23.10	1.00	12.00
5A	6-May-91	0.08	30	100	3	FA	8840	200	5.85	18133.33	530.40	0.37	4.44
5A	6-May-91	0.08	30	100	4	FA	8940	200	5.85	18338.46	536.40	0.39	4.68
5B	6-May-91	0.08	30	100	1	PA	17025	200	8.91	22929.29	1021.50	21.50	258.00
5B	6-May-91	0.08	30	100	2	FA	572	200	8.91	770.37	34.32	1.00	12.00
5B	6-May-91	0.08	30	100	3	FA	13021	200	8.91	17536.70	781.26	0.33	3.96
5B	6-May-91	0.08	30	100	4	FA	13048	200	8.91	17573.06	782.88	0.35	4.20

Run No.	Date Complete	Current (micro-amps)	Energy (MeV)	Slit Width	Radiac No.	Radiac Status	Counts	Clicks	Minutes	CPM per microamp	CPC per microamp	mrem per hour	mrem per hour per microamp
5C	6-May-91	0.08	30	100	1	PA	15307	200	9.08	20229.52	918.42	21.50	258.00
5C	6-May-91	0.08	30	100	2	FA	493	200	9.08	651.54	29.58	1.00	12.00
5C	6-May-91	0.08	30	100	3	FA	12076	200	9.08	15959.47	724.56	0.33	3.96
5C	6-May-91	0.08	30	100	4	FA	12124	200	9.08	16022.91	727.44	0.32	3.84
6A	14-May-91	0.25	30	100	1	D	7206	200	6.21	4641.55	144.12	12.00	48.00
6A	14-May-91	0.25	30	100	2	D	8321	200	6.21	5359.74	166.42	10.50	42.00
6A	14-May-91	0.25	30	100	3	FA	6031	200	6.21	3884.70	120.62	0.18	0.72
6A	14-May-91	0.25	30	100	4	FA	5955	200	6.21	3835.75	119.10	0.20	0.80
6B	14-May-91	0.25	30	100	1	D	7102	200	5.92	4798.65	142.04	13.50	54.00
6B	14-May-91	0.25	30	100	2	D	8581	200	5.92	5797.97	171.62	13.20	52.80
6B	14-May-91	0.25	30	100	3	FA	6017	200	5.92	4065.54	120.34	0.22	0.88
6B	14-May-91	0.25	30	100	4	FA	5908	200	5.92	3991.89	118.16	0.19	0.76
6C	14-May-91	0.25	30	100	1	D	8847	200	7.15	4949.37	176.94	13.50	54.00
6C	14-May-91	0.25	30	100	2	D	10639	200	7.15	5951.89	212.78	13.30	53.20
6C	14-May-91	0.25	30	100	3	FA	7841	200	7.15	4386.57	156.82	0.22	0.88
6C	14-May-91	0.25	30	100	4	FA	7298	200	7.15	4082.80	145.96	0.21	0.84
7A	29-Apr-91	0.21	60	300	1	FA	656	328	10.00	314.88	9.60	0.50	2.40
7A	29-Apr-91	0.21	60	300	2	PA	21489	328	10.00	10314.72	314.47	19.00	91.20
7A	29-Apr-91	0.21	60	300	3	FA	UNK	UNK	UNK	UNK	UNK	0.30	1.44
7A	29-Apr-91	0.21	60	300	4	FA	UNK	UNK	UNK	UNK	UNK	0.30	1.44
7B	29-Apr-91	0.21	60	300	1	FA	625	284	10.00	300.00	10.56	0.50	2.40
7B	29-Apr-91	0.21	60	300	2	PA	20082	284	10.00	9639.36	339.41	18.00	86.40
7B	29-Apr-91	0.21	60	300	3	FA	UNK	UNK	UNK	UNK	UNK	0.30	1.44
7B	29-Apr-91	0.21	60	300	4	FA	UNK	UNK	UNK	UNK	UNK	0.28	1.34
7C	29-Apr-91	0.21	60	300	1	FA	681	303	10.00	326.88	10.79	0.50	2.40
7C	29-Apr-91	0.21	60	300	2	PA	20273	303	10.00	9731.04	321.16	17.00	81.60
7C	29-Apr-91	0.21	60	300	3	FA	UNK	UNK	UNK	UNK	UNK	0.34	1.63
7C	29-Apr-91	0.21	60	300	4	FA	UNK	UNK	UNK	UNK	UNK	0.27	1.30

Run No.	Date Complete	Current (micro-amps)	Energy (MeV)	Slit Width	Radiac No.	Radiac Status	Counts	Clicks	Minutes	CPM per microamp	CPC per microamp	mrem per hour	mrem per hour per microamp
8A	29-Apr-91	0.21	60	300	1	PA	5230	200	4.09	6137.90	125.52	13.50	64.80
8A	29-Apr-91	0.21	60	300	2	FA	165	200	4.09	193.64	3.96	0.60	2.88
8A	29-Apr-91	0.21	60	300	3	FA	4456	200	4.09	5229.54	106.94	0.20	0.96
8A	29-Apr-91	0.21	60	300	4	FA	4449	200	4.09	5221.32	106.78	0.22	1.06
8B	29-Apr-91	0.21	60	300	1	PA	5067	200	3.86	6300.93	121.61	15.00	72.00
8B	29-Apr-91	0.21	60	300	2	FA	143	200	3.86	177.82	3.43	0.50	2.40
8B	29-Apr-91	0.21	60	300	3	FA	4295	200	3.86	5340.93	103.08	0.25	1.20
8B	29-Apr-91	0.21	60	300	4	FA	4371	200	3.86	5435.44	104.90	0.26	1.25
8C	29-Apr-91	0.21	60	300	1	PA	5225	200	4.08	6147.06	125.40	13.00	62.40
8C	29-Apr-91	0.21	60	300	2	FA	139	200	4.08	163.53	3.34	0.40	1.92
8C	29-Apr-91	0.21	60	300	3	FA	4960	200	4.08	5835.29	119.04	0.25	1.20
8C	29-Apr-91	0.21	60	300	4	FA	4416	200	4.08	5195.29	105.98	0.23	1.10
9A	1-May-91	0.25	60	300	1	D	5480	200	4.53	4838.85	109.60	13.00	52.00
9A	1-May-91	0.25	60	300	2	D	6034	200	4.53	5328.04	120.68	12.50	50.00
9A	1-May-91	0.25	60	300	3	FA	4670	200	4.53	4123.62	93.40	0.20	0.80
9A	1-May-91	0.25	60	300	4	FA	4781	200	4.53	4221.63	95.62	0.23	0.92
9B	1-May-91	0.25	60	300	1	D	10198	200	8.16	4999.02	203.96	13.50	54.00
9B	1-May-91	0.25	60	300	2	D	11329	200	8.16	5553.43	226.58	13.50	54.00
9B	1-May-91	0.25	60	300	3	FA	8964	200	8.16	4394.12	179.28	0.23	0.92
9B	1-May-91	0.25	60	300	4	FA	8742	200	8.16	4285.29	174.84	0.22	0.88
9C	1-May-91	0.25	60	300	1	D	11147	200	8.56	5208.88	222.94	14.00	56.00
9C	1-May-91	0.25	60	300	2	D	12282	200	8.56	5739.25	245.64	12.00	48.00
9C	1-May-91	0.25	60	300	3	FA	9861	200	8.56	4607.94	197.22	0.27	1.08
9C	1-May-91	0.25	60	300	4	FA	9687	200	8.56	4526.64	193.74	0.28	1.12
10A	1-May-91	0.25	60	100	1	FA	334	200	10.22	130.72	6.68	0.10	0.40
10A	1-May-91	0.25	60	100	2	PA	9617	200	10.22	3763.99	192.34	6.00	24.00
10A	1-May-91	0.25	60	100	3	FA	7338	200	10.22	2872.02	146.76	0.14	0.56
10A	1-May-91	0.25	60	100	4	FA	7149	200	10.22	2798.04	142.98	0.15	0.60

Run No.	Date Complete	Current (micro-amps)	Energy (MeV)	Slit Width	Radiac No.	Radiac Status	Counts	Clicks	Minutes	CPM per microamp	CPC per microamp	mrem per hour	mrem per hour per microamp
10B	1-May-91	0.25	60	100	1	FA	193	200	5.50	140.36	3.86	0.20	0.80
10B	1-May-91	0.25	60	100	2	PA	5530	200	5.50	4021.82	110.60	10.00	40.00
10B	1-May-91	0.25	60	100	3	FA	4339	200	5.50	3155.64	86.78	0.20	0.80
10B	1-May-91	0.25	60	100	4	FA	4101	200	5.50	2982.55	82.02	0.19	0.76
10C	1-May-91	0.25	60	100	1	FA	505	200	14.03	143.98	10.10	0.20	0.80
10C	1-May-91	0.25	60	100	2	PA	15857	200	14.03	4520.88	317.14	10.00	40.00
10C	1-May-91	0.25	60	100	3	FA	12346	200	14.03	3519.89	246.92	0.20	0.80
10C	1-May-91	0.25	60	100	4	FA	11979	200	14.03	3415.25	239.58	0.21	0.84
11A	1-May-91	0.25	60	100	1	PA	15126	200	13.93	4343.43	302.52	10.50	42.00
11A	1-May-91	0.25	60	100	2	FA	417	200	13.93	119.74	8.34	0.40	1.60
11A	1-May-91	0.25	60	100	3	FA	12609	200	13.93	3620.67	252.18	0.22	0.88
11A	1-May-91	0.25	60	100	4	FA	12436	200	13.93	3571.00	248.72	0.22	0.88
11B	1-May-91	0.25	60	100	1	PA	24342	200	16.87	5771.67	486.84	16.00	64.00
11B	1-May-91	0.25	60	100	2	FA	714	200	16.87	169.29	14.28	0.50	2.00
11B	1-May-91	0.25	60	100	3	FA	20284	200	16.87	4809.48	405.68	0.26	1.04
11B	1-May-91	0.25	60	100	4	FA	20223	200	16.87	4795.02	404.46	0.26	1.04
11C	1-May-91	0.25	60	100	1	PA	12529	200	9.19	5453.32	250.58	13.50	54.00
11C	1-May-91	0.25	60	100	2	FA	356	200	9.19	154.95	7.12	0.50	2.00
11C	1-May-91	0.25	60	100	3	FA	10840	200	9.19	4718.17	216.80	0.18	0.72
11C	1-May-91	0.25	60	100	4	FA	10360	200	9.19	4509.25	207.20	0.21	0.84
12A	6-May-91	0.08	60	100	1	D	5596	200	5.19	12938.73	335.76	11.00	132.00
12A	6-May-91	0.08	60	100	2	D	5979	200	5.19	13824.28	358.74	10.50	126.00
12A	6-May-91	0.08	60	100	3	FA	4999	200	5.19	11558.38	299.94	0.23	2.76
12A	6-May-91	0.08	60	100	4	FA	4542	200	5.19	10501.73	272.52	0.22	2.64
12B	6-May-91	0.08	60	100	1	D	5344	200	4.67	13731.91	320.64	11.50	138.00
12B	6-May-91	0.08	60	100	2	D	5854	200	4.67	15042.40	351.24	11.50	138.00
12B	6-May-91	0.08	60	100	3	FA	4281	200	4.67	11000.43	256.86	0.21	2.52
12B	6-May-91	0.08	60	100	4	FA	4370	200	4.67	11229.12	262.20	0.20	2.40

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12C	6-May-91	0.08	60	100	1	D	5589	200	4.90	13687.35	335.34	11.00	132.00
12C	6-May-91	0.08	60	100	2	D	6081	200	4.90	14892.24	364.86	11.80	141.60
12C	6-May-91	0.08	60	100	3	FA	4735	200	4.90	11595.92	284.10	0.22	2.64
12C	6-May-91	0.08	60	100	4	FA	4723	200	4.90	11566.53	283.38	0.20	2.40
13A	13-May-91	0.17	90	300	1	FA	263	200	9.09	173.60	7.89	0.50	3.00
13A	13-May-91	0.17	90	300	2	PA	8558	200	9.09	5648.84	256.74	8.00	48.00
13A	13-May-91	0.17	90	300	3	FA	6461	200	9.09	4264.69	193.83	0.16	0.96
13A	13-May-91	0.17	90	300	4	FA	6268	200	9.09	4137.29	188.04	0.15	0.90
13B	13-May-91	0.17	90	300	1	FA	127	200	5.29	144.05	3.81	0.25	1.50
13B	13-May-91	0.17	90	300	2	PA	4734	200	5.29	5369.38	142.02	7.50	45.00
13B	13-May-91	0.17	90	300	3	FA	3849	200	5.29	4365.60	115.47	0.14	0.84
13B	13-May-91	0.17	90	300	4	FA	3679	200	5.29	4172.78	110.37	0.15	0.90
13C	13-May-91	0.17	90	300	1	FA	115	200	4.59	150.33	3.45	0.50	3.00
13C	13-May-91	0.17	90	300	2	PA	3865	200	4.59	5052.29	115.95	7.50	45.00
13C	13-May-91	0.17	90	300	3	FA	3028	200	4.59	3958.17	90.84	0.14	0.84
13C	13-May-91	0.17	90	300	4	FA	2952	200	4.59	3858.82	88.56	0.15	0.90
14A	13-May-91	0.17	90	300	1	PA	8794	200	7.17	7359.00	263.82	13.50	81.00
14A	13-May-91	0.17	90	300	2	FA	262	200	7.17	219.25	7.86	0.50	3.00
14A	13-May-91	0.17	90	300	3	FA	6980	200	7.17	5841.00	209.40	0.21	1.26
14A	13-May-91	0.17	90	300	4	FA	7019	200	7.17	5873.64	210.57	0.21	1.26
14B	13-May-91	0.17	90	300	1	PA	5724	200	5.65	6078.58	171.72	12.00	72.00
14B	13-May-91	0.17	90	300	2	FA	187	200	5.65	198.58	5.61	0.60	3.60
14B	13-May-91	0.17	90	300	3	FA	4438	200	5.65	4712.92	133.14	0.20	1.20
14B	13-May-91	0.17	90	300	4	FA	4527	200	5.65	4807.43	135.81	0.21	1.26
14C	13-May-91	0.17	90	300	1	PA	4979	200	4.97	6010.87	149.37	11.00	66.00
14C	13-May-91	0.17	90	300	2	FA	115	200	4.97	138.83	3.45	0.50	3.00
14C	13-May-91	0.17	90	300	3	FA	3824	200	4.97	4616.50	114.72	0.18	1.08
14C	13-May-91	0.17	90	300	4	FA	3708	200	4.97	4476.46	111.24	0.19	1.14

Run No.	Date Complete	Current (micro-amps)	Energy (MeV)	Slit Width	Radiac No.	Radiac Status	Counts	Clicks	Minutes	CPM per microamp	CPC per microamp	mrem per hour	mrem per hour per microamp
15A	13-May-91	0.17	90	300	1	D	3543	200	3.98	5341.21	106.29	9.50	57.00
15A	13-May-91	0.17	90	300	2	D	3995	200	3.98	6022.61	119.85	9.50	57.00
15A	13-May-91	0.17	90	300	3	FA	2877	200	3.98	4337.19	86.31	0.21	1.26
15A	13-May-91	0.17	90	300	4	FA	2900	200	3.98	4371.86	87.00	0.18	1.08
15B	13-May-91	0.17	90	300	1	D	3743	200	4.82	4659.34	112.29	9.00	54.00
15B	13-May-91	0.17	90	300	2	D	4148	200	4.82	5163.49	124.44	9.00	54.00
15B	13-May-91	0.17	90	300	3	FA	3086	200	4.82	3841.49	92.58	0.19	1.14
15B	13-May-91	0.17	90	300	4	FA	2989	200	4.82	3720.75	89.67	0.17	1.02
15C	13-May-91	0.17	90	300	1	D	3787	200	4.23	5371.63	113.61	9.50	57.00
15C	13-May-91	0.17	90	300	2	D	4450	200	4.23	6312.06	133.50	9.00	54.00
15C	13-May-91	0.17	90	300	3	FA	3166	200	4.23	4490.78	94.98	0.17	1.02
15C	13-May-91	0.17	90	300	4	FA	3195	200	4.23	4531.91	95.85	0.18	1.08
16A	13-May-91	0.17	90	100	1	FA	135	200	4.10	197.56	4.05	0.40	2.40
16A	13-May-91	0.17	90	100	2	PA	4163	200	4.10	6092.20	124.89	8.50	51.00
16A	13-May-91	0.17	90	100	3	FA	3072	200	4.10	4495.61	92.16	0.14	0.84
16A	13-May-91	0.17	90	100	4	FA	2984	200	4.10	4366.83	89.52	0.15	0.90
16B	13-May-91	0.17	90	100	1	FA	136	200	4.31	189.33	4.08	0.40	2.40
16B	13-May-91	0.17	90	100	2	PA	5103	200	4.31	7103.94	153.09	11.00	66.00
16B	13-May-91	0.17	90	100	3	FA	3779	200	4.31	5260.79	113.37	0.19	1.14
16B	13-May-91	0.17	90	100	4	FA	3653	200	4.31	5085.38	109.59	0.18	1.08
16C	13-May-91	0.17	90	100	1	FA	158	200	4.41	214.97	4.74	0.50	3.00
16C	13-May-91	0.17	90	100	2	PA	4952	200	4.41	6737.41	148.56	11.00	66.00
16C	13-May-91	0.17	90	100	3	FA	3789	200	4.41	5155.10	113.67	0.18	1.08
16C	13-May-91	0.17	90	100	4	FA	3701	200	4.41	5035.37	111.03	0.19	1.14
17A	13-May-91	0.17	90	100	1	PA	4372	200	4.11	6382.48	131.16	11.00	66.00
17A	13-May-91	0.17	90	100	2	FA	136	200	4.11	198.54	4.08	0.50	3.00
17A	13-May-91	0.17	90	100	3	FA	3471	200	4.11	5067.15	104.13	0.17	1.02
17A	13-May-91	0.17	90	100	4	FA	3355	200	4.11	4897.81	100.65	0.16	0.96

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17B	13-May-91	0.17	90	100	1	PA	4879	200	4.29	6823.78	146.37	12.00	72.00
17B	13-May-91	0.17	90	100	2	FA	161	200	4.29	225.17	4.83	0.60	3.60
17B	13-May-91	0.17	90	100	3	FA	3889	200	4.29	5439.16	116.67	0.19	1.14
17B	13-May-91	0.17	90	100	4	FA	3923	200	4.29	5486.71	117.69	0.20	1.20
17C	13-May-91	0.17	90	100	1	PA	5307	200	4.39	7253.30	159.21	16.00	96.00
17C	13-May-91	0.17	90	100	2	FA	150	200	4.39	205.01	4.50	0.50	3.00
17C	13-May-91	0.17	90	100	3	FA	4285	200	4.39	5856.49	128.55	0.21	1.26
17C	13-May-91	0.17	90	100	4	FA	4147	200	4.39	5667.88	124.41	0.21	1.26
18A	13-May-91	0.17	90	100	1	D	3666	200	3.95	5568.61	109.98	10.00	60.00
18A	13-May-91	0.17	90	100	2	D	4042	200	3.95	6139.75	121.26	9.50	57.00
18A	13-May-91	0.17	90	100	3	FA	3189	200	3.95	4844.05	95.67	0.17	1.02
18A	13-May-91	0.17	90	100	4	FA	2925	200	3.95	4443.04	87.75	0.15	0.90
18B	13-May-91	0.17	90	100	1	D	3643	200	4.05	5397.04	109.29	9.00	54.00
18B	13-May-91	0.17	90	100	2	D	4152	200	4.05	6151.11	124.56	9.50	57.00
18B	13-May-91	0.17	90	100	3	FA	3077	200	4.05	4558.52	92.31	0.18	1.08
18B	13-May-91	0.17	90	100	4	FA	3243	200	4.05	4804.44	97.29	0.19	1.14
18C	13-May-91	0.17	90	100	1	D	3781	200	4.01	5657.36	113.43	10.00	60.00
18C	13-May-91	0.17	90	100	2	D	4142	200	4.01	6197.51	124.26	9.20	55.20
18C	13-May-91	0.17	90	100	3	FA	3110	200	4.01	4653.37	93.30	0.18	1.08
18C	13-May-91	0.17	90	100	4	FA	3104	200	4.01	4644.39	93.12	0.20	1.20
19A	14-May-91	0.25	60	300	1	FA	289	200	7.89	146.51	5.78	0.25	1.00
19A	14-May-91	0.25	60	300	2	PA	10421	200	7.89	5283.14	208.42	10.00	40.00
19A	14-May-91	0.25	60	300	3	FA	7483	200	7.89	3793.66	149.66	0.18	0.72
19A	14-May-91	0.25	60	300	4	FA	7249	200	7.89	3675.03	144.98	0.19	0.76
19B	14-May-91	0.25	60	300	1	FA	289	200	6.95	166.33	5.78	0.35	1.40
19B	14-May-91	0.25	60	300	2	PA	10421	200	6.95	5997.70	208.42	11.00	44.00
19B	14-May-91	0.25	60	300	3	FA	7483	200	6.95	4306.76	149.66	0.19	0.76
19B	14-May-91	0.25	60	300	4	FA	7249	200	6.95	4172.09	144.98	0.18	0.72

APPENDIX H: AN/PDR-70 (#2) CORRECTED READINGS

Definition of terms and abbreviations:

- Radiac #2 Reading (cpm) = data from Appendix G for AN/PDR-70 serial number A-67, in counts per minute
- Ratio Correction Term = data from Table D1
- Corrected Reading (cpm) = reading of radiac number two, in counts per minute, in radiac number one units

APPENDIX H: AN/PDR-70 (#2) CORRECTED READINGS

Definition of terms and abbreviations:

- Radiac #2 Reading (cpm) = data from Appendix G for AN/PDR-70 serial number A-67, in counts per minute
- Ratio Correction Term = data from Table D1
- Corrected Reading (cpm) = reading of radiac number two, in counts per minute, in radiac number one units

Run No.	Radiac #2 Reading (cpm)	AN/PDR-70 Ratio Correction Term	Radiac #2 Corrected Reading (cpm)
1A	1636.36	0.88	1440.00
1B	1650.54	0.88	1452.48
1C	1557.41	0.88	1370.52
2A	57.07	0.88	50.22
2B	50.96	0.88	44.84
2C	56.22	0.88	49.47
4A	1883.30	0.84	1581.97
4B	1925.54	0.84	1617.45
4C	2162.74	0.84	1816.70
5A	65.81	0.84	55.28
5B	64.20	0.84	53.93
5C	54.30	0.84	45.61
7A	2148.90	0.91	1955.50
7B	2008.20	0.91	1827.46
7C	2027.30	0.91	1844.84
8A	40.34	0.91	36.71
8B	37.05	0.91	33.72
8C	34.07	0.91	31.00
10A	941.00	0.92	865.72
10B	1005.45	0.92	925.01
10C	1130.22	0.92	1039.80
11A	29.94	0.92	27.54
11B	42.32	0.92	38.93
11C	38.74	0.92	35.64
13A	941.47	0.88	828.49
13B	894.90	0.88	787.51
13C	842.05	0.88	741.00
14A	36.54	0.88	32.16
14B	33.10	0.88	29.13
14C	23.14	0.88	20.36
16A	1015.37	0.90	913.83
16B	1183.99	0.90	1065.59
16C	1122.90	0.90	1010.61
17A	33.09	0.90	29.78
17B	37.53	0.90	33.78
17C	34.17	0.90	30.75
19A	1320.79	0.91	1201.92
19B	1499.42	0.91	1364.47
19C	1337.50	0.91	1217.13

APPENDIX I: RUN SPECIFIC THERMOLUMINESCENT DOSIMETER NEUTRON ENERGY CORRECTION FACTOR

Definition of terms and abbreviations:

- Radiac (number) Reading (cpm) = data from Appendix G for radiac number one and from Appendix H for radiac number two, in counts per minute
- PA/FA = ratio of the reading of the partially assembled radiac to the reading of the fully assembled radiac
- TLD NECF = calculated factor using formula of Section III.A

Run No.	Radiac #1 Reading (cpm)	Radiac #2 Reading (cpm)	PA/FA	TLD NECF
1A	57.09	1440.00	25	0.45
1B	60.51	1452.48	24	0.47
1C	57.91	1370.52	24	0.48
2A	1756.53	50.22	35	0.33
2B	1590.93	44.84	35	0.32
2C	1663.09	49.47	34	0.34
4A	68.30	1581.97	23	0.49
4B	68.72	1617.45	24	0.48
4C	77.10	1816.70	24	0.48
5A	1914.19	55.28	35	0.33
5B	1910.77	53.93	35	0.32
5C	1685.79	45.61	37	0.31
7A	65.60	1955.50	30	0.38
7B	62.50	1827.46	29	0.39
7C	68.10	1844.84	27	0.42
8A	1278.73	36.71	35	0.33
8B	1312.69	33.72	39	0.29
8C	1280.64	31.00	41	0.28
10A	32.68	865.72	26	0.43
10B	35.09	925.01	26	0.43
10C	35.99	1039.80	29	0.39
11A	1085.86	27.54	39	0.29
11B	1442.92	38.93	37	0.31
11C	1363.33	35.64	38	0.30
13A	28.93	828.49	29	0.40
13B	24.01	787.51	33	0.35
13C	25.05	741.00	30	0.39
14A	1226.50	32.16	38	0.30
14B	1013.10	29.13	35	0.33
14C	1001.81	20.36	49	0.23
16A	32.93	913.83	28	0.41
16B	31.55	1065.59	34	0.34
16C	35.83	1010.61	28	0.40
17A	1063.75	29.78	36	0.32
17B	1137.30	33.78	34	0.34
17C	1208.88	30.75	39	0.29
19A	36.63	1201.92	33	0.35
19B	41.58	1364.47	33	0.35
19C	43.02	1217.13	28	0.40

APPENDIX J: NAVAL DOSIMETRY CENTER EVALUATION OF NEUTRON ENERGY CORRECTION FACTOR

Reproduced in this Appendix is a letter received from the Officer in Charge of the Naval Dosimetry Center that is concerned with the same topics as this thesis. To summarize, the Naval Dosimetry Center is in agreement that the neutron dose evaluation may be being overestimated for LINAC operating personnel. This is because the neutron energy correction factor's default value (5.2) is suggested to be "overly conservative," both by the studies and experiments of the author and by the evaluations of the Naval Dosimetry Center. However, for the reasons that are stated in the letter, the Officer in Charge of the Naval Dosimetry Center does not believe that the neutron energy correction factor assigned to the Naval Postgraduate School's linear accelerator can be justifiably changed "at this time."

DEPARTMENT OF THE NAVY
NAVY ENVIRONMENTAL HEALTH CENTER DETACHMENT
NAVAL DOSIMETRY CENTER
BETHESDA, MD 20889-5000

IN REPLY REFER TO

6470
Ser 00/00042
29 Apr 92

From: Officer in Charge, Naval Dosimetry Center, Navy Environmental Health Center Detachment, Bethesda, MD 20889-5614
To: Commanding Officer, Naval Post Graduate School, Monterey, CA 93943

Subj: PERSONNEL NEUTRON DOSIMETRY EVALUATIONS

1. For over a year your Professor Maruyama and my LCDR S. Doremus, MSC, USN have been assessing neutron exposures received by personnel operating your pulsed Linear Accelerator (LINAC). There is concern that the neutron dose evaluations performed by the Dosimetry Center for these personnel overestimate the true dose. An overestimate of the true dose is conceivable because we apply a default neutron energy correction factor of 5.2, corresponding to a relatively hard neutron energy spectrum, to the dosimeter reading to correct for the energy spectrum of the beam. Exposures from a lower energy or more moderated spectrum would be over-reported by this procedure. A default value is applied because the neutron energy spectrum of the LINAC is unknown. The energy spectrum is difficult to quantify because the pulsed nature of the field is quicker than the response time of currently approved electronic detection systems. The default factor is usually very conservative for neutron sources used in the Navy but ensures personnel exposures are not understated.

2. Two efforts have been initiated to determine a specific neutron energy correction factor for your LINAC facility.

a. First, two BUMED Area Monitors (BAMs) were installed at locations occupied by personnel during LINAC operations. The BAM is a recognized standard for measuring the "true" rem dose. It is an analog of the AN/PDR-70 neutron rem-meter and can integrate the total neutron dose from a pulsed source. A comparison of the BAM results and personnel doses (i.e., the individual receiving the highest neutron exposure) should provide some indicator of the extent personnel doses are being overestimated. Review of the data in Table I of enclosure (1) indicates the average maximum personnel exposure is approximately 7 times the exposure determined from the BAM. This comparison is limited because there is no guarantee the workers were exposed at the same location as the BAM or for the same amount of time.

b. To correct for the possible difference in time and location of exposure, TLDs were posted on the face of the BAMs for comparison with the measurement by the BAM. These results are displayed in Table II of enclosure (1). Unfortunately only one exposure period, 20 August 1991, recorded enough exposure on the BAM to make a comparison. This single data point indicates the personnel exposures are approximately 3.4 times the exposure determined from the BAM. This comparison is limited because it is not known how closely a badge posted on the surface of a BAM represents a badge worn by worker and because of the potential error involved with a single data point.

3. Both of the above methods suggest the default neutron energy correction factor being used is overly conservative. However, I do not believe the data is sufficient, nor the current personnel exposures particularly high, to justify changing from the default neutron energy correction factor at this time. I recommend TLDs continue to be posted on the outer surface of the BAMs to expand the data base for determining a neutron energy correction factor specific to your facility. If you have any questions, my point of contact is LCDR Steve Doremus, MSC, USN, who may be reached on DVN 295-5422 or (301) 295-5422.

J. D. George
J. D. GEORGE

Copy to:
BUMED
NSWC, R41 (Mr. Gordan Reel)

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